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(12) **United States Patent**
Kusunoki et al.

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(45) **Date of Patent: Oct. 9, 2018**

(54) **WIRELESS POWER TRANSMISSION SYSTEM FOR TRANSMITTING ALTERNATING-CURRENT POWER WIRELESSLY**

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(72) Inventors: **Masahiro Kusunoki**, Tokyo (JP); **Mitsuru Masuda**, Tokyo (JP)

(73) Assignee: **FURUKAWA ELECTRIC CO., LTD.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 436 days.

(21) Appl. No.: **14/813,074**

(22) Filed: **Jul. 29, 2015**

(65) **Prior Publication Data**

US 2015/0333539 A1 Nov. 19, 2015

Related U.S. Application Data

(63) Continuation of application No. PCT/JP2013/081826, filed on Nov. 27, 2013.

(30) **Foreign Application Priority Data**

Jan. 31, 2013 (JP) 2013-017774

(51) **Int. Cl.**
H02J 5/00 (2016.01)
H02J 50/12 (2016.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H02J 50/12*** (2016.02); ***H02J 5/005*** (2013.01); ***H02J 7/025*** (2013.01); ***H02J 50/05*** (2016.02)

(58) **Field of Classification Search**
CPC . H02J 5/005; H02J 50/05; H02J 17/00; H04B 5/0037; H04B 5/0012
See application file for complete search history.

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Assistant Examiner — Michael Warmflash
(74) *Attorney, Agent, or Firm* — Amin, Turocy & Watson, LLP

(57) **ABSTRACT**

[OBJECT] There is provided a wireless power transmission system capable of transmitting power efficiently even when it is rotated.

[ORGANIZATION] A power transmission device has a first and a second electrode (a center electrode **311** and an annular electrode **312**) each having a rotationally symmetrical shape with respect to a common center axis, a first and a second connection line (connection lines **315**, **316**), and a first inductor to (inductor **313**, **314**). A power reception device has a third and a fourth electrode (center electrode **321** and annular electrode **322**) each having a rotationally symmetrical shape with respect to a common center axis, a third and a fourth connection line (connection lines **325**, **326**), and a second inductor. The electrodes of the power transmission device and the power reception device are disposed to oppose each other across a distance of λ/2π or less as a near field, and a resonance frequency of a coupler constituted of the first and the second electrode and the first inductor and a resonance frequency of a coupler constituted

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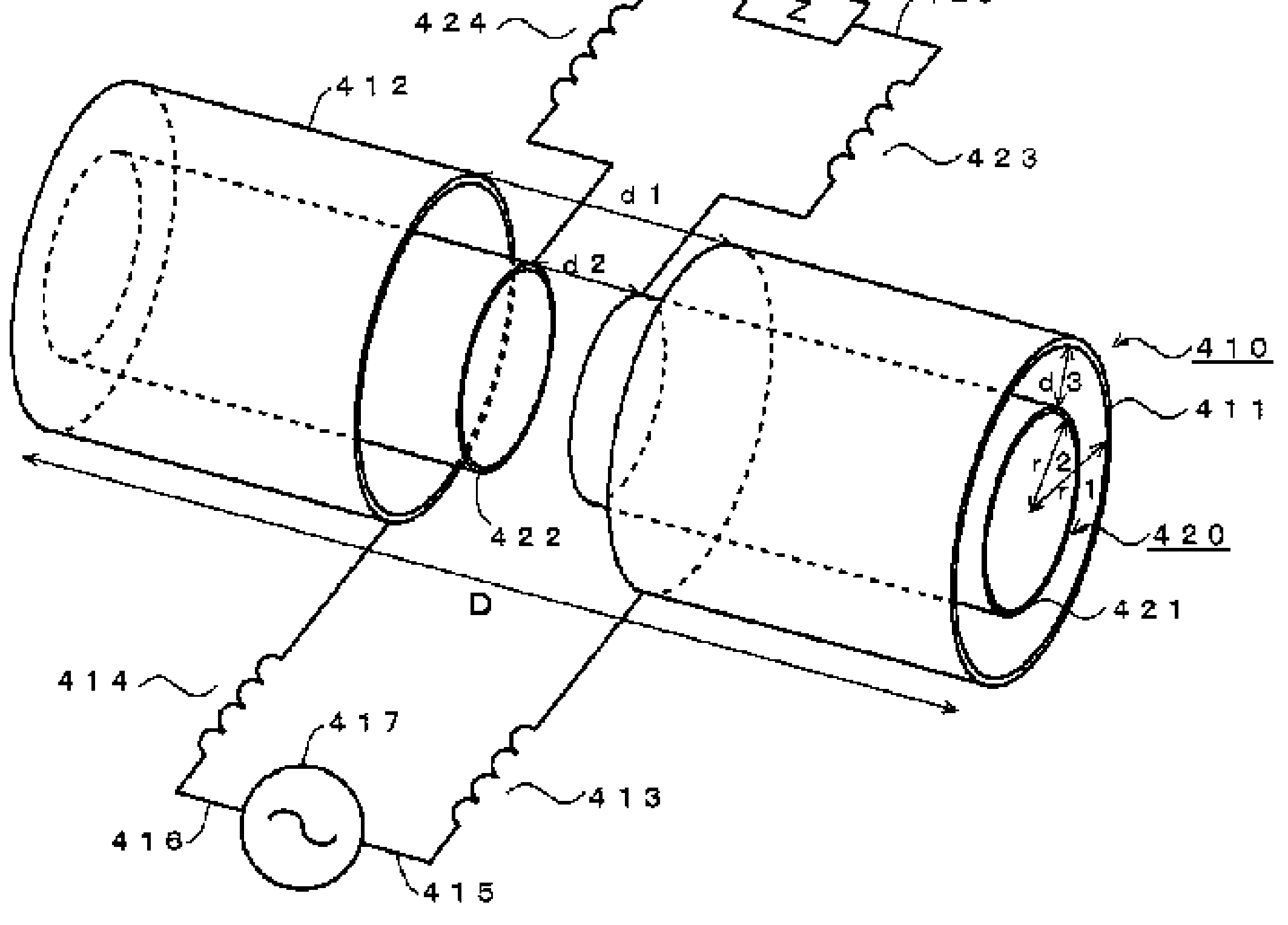

of the third and the fourth electrode and the second inductor (inductor **323**, **324**) are set to be substantially equal.

4 Claims, 30 Drawing Sheets

(51) **Int. Cl.**

H02J 7/02	(2016.01)
H02J 50/05	(2016.01)

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FIG.1

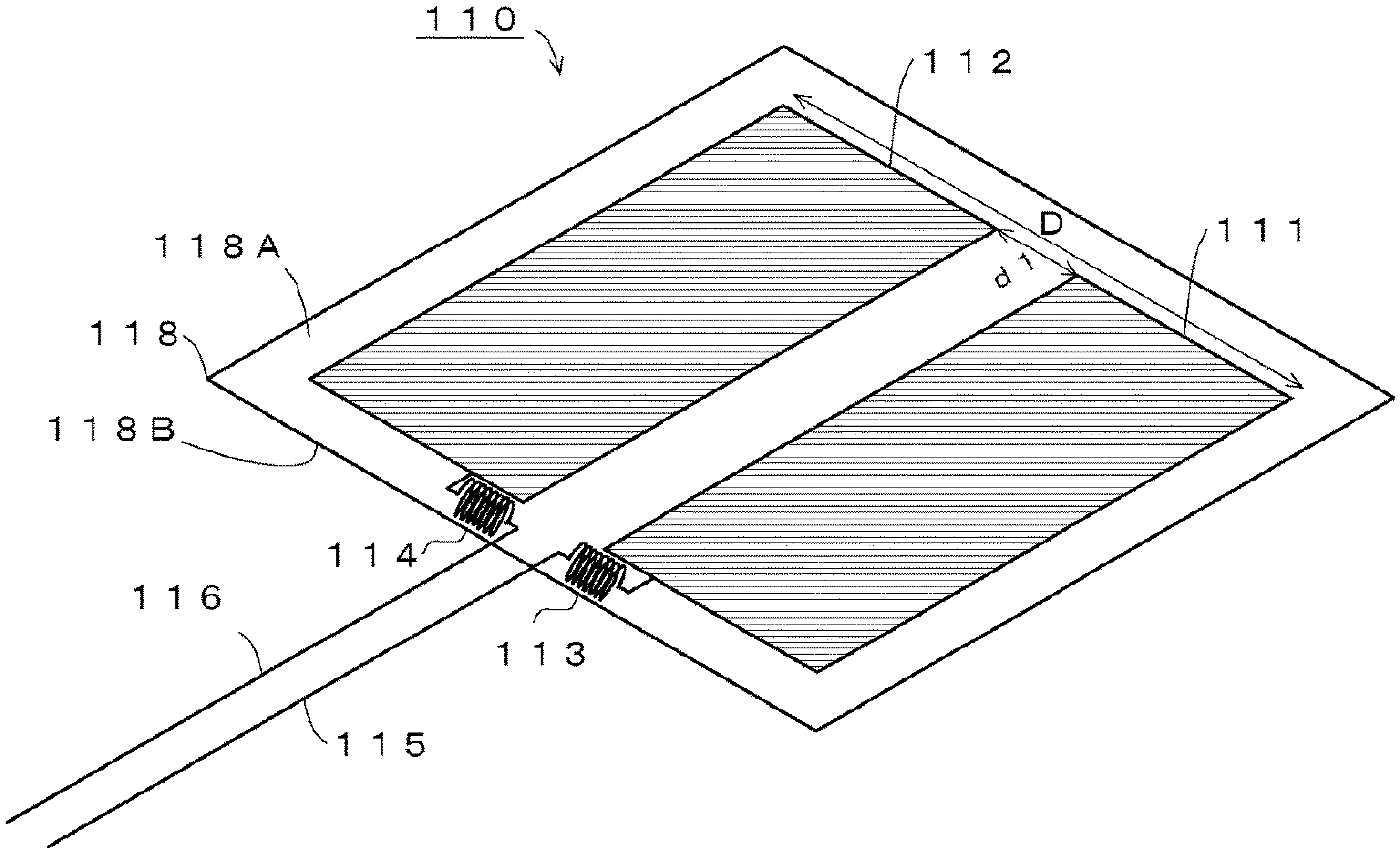

FIG.2

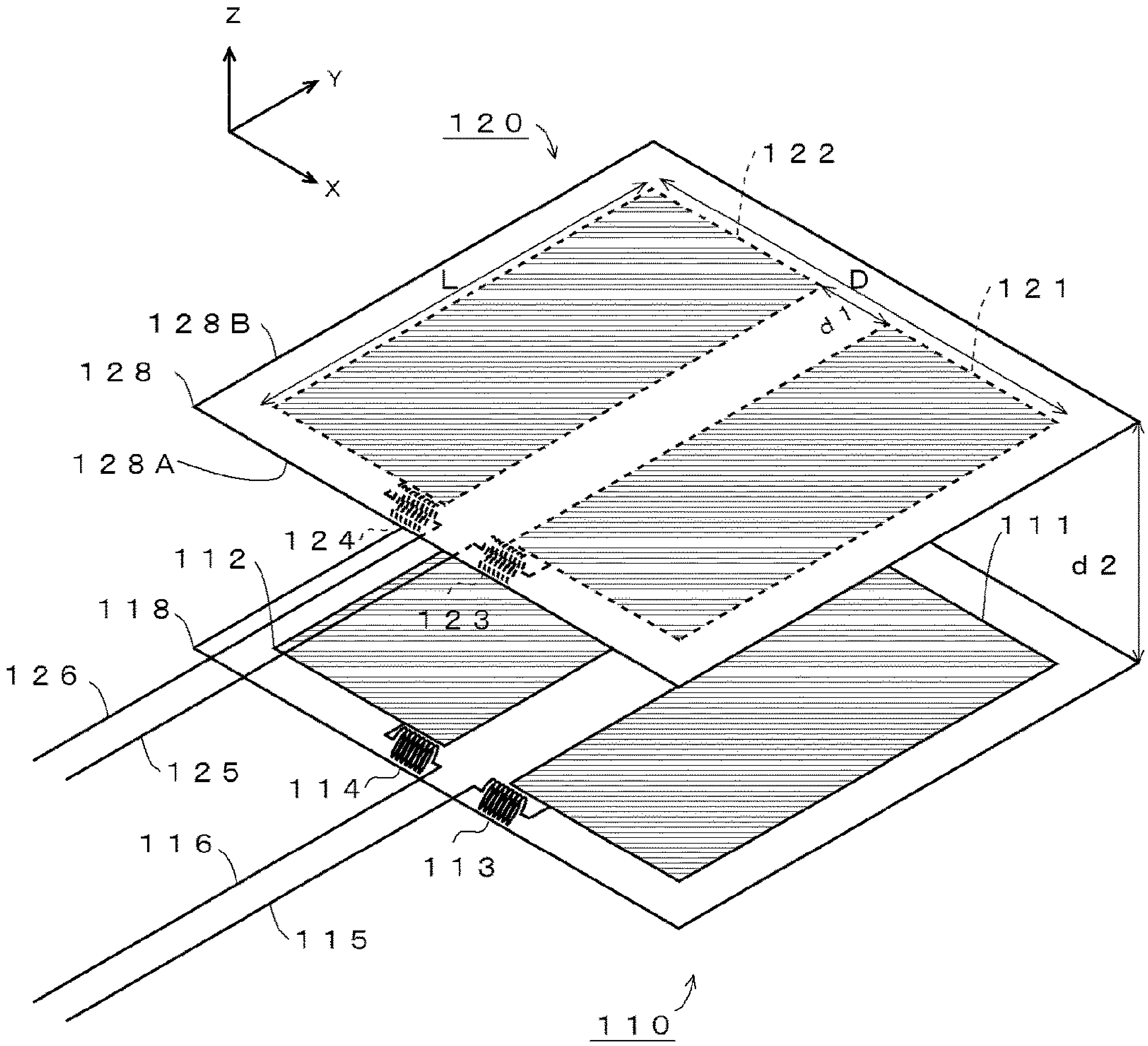
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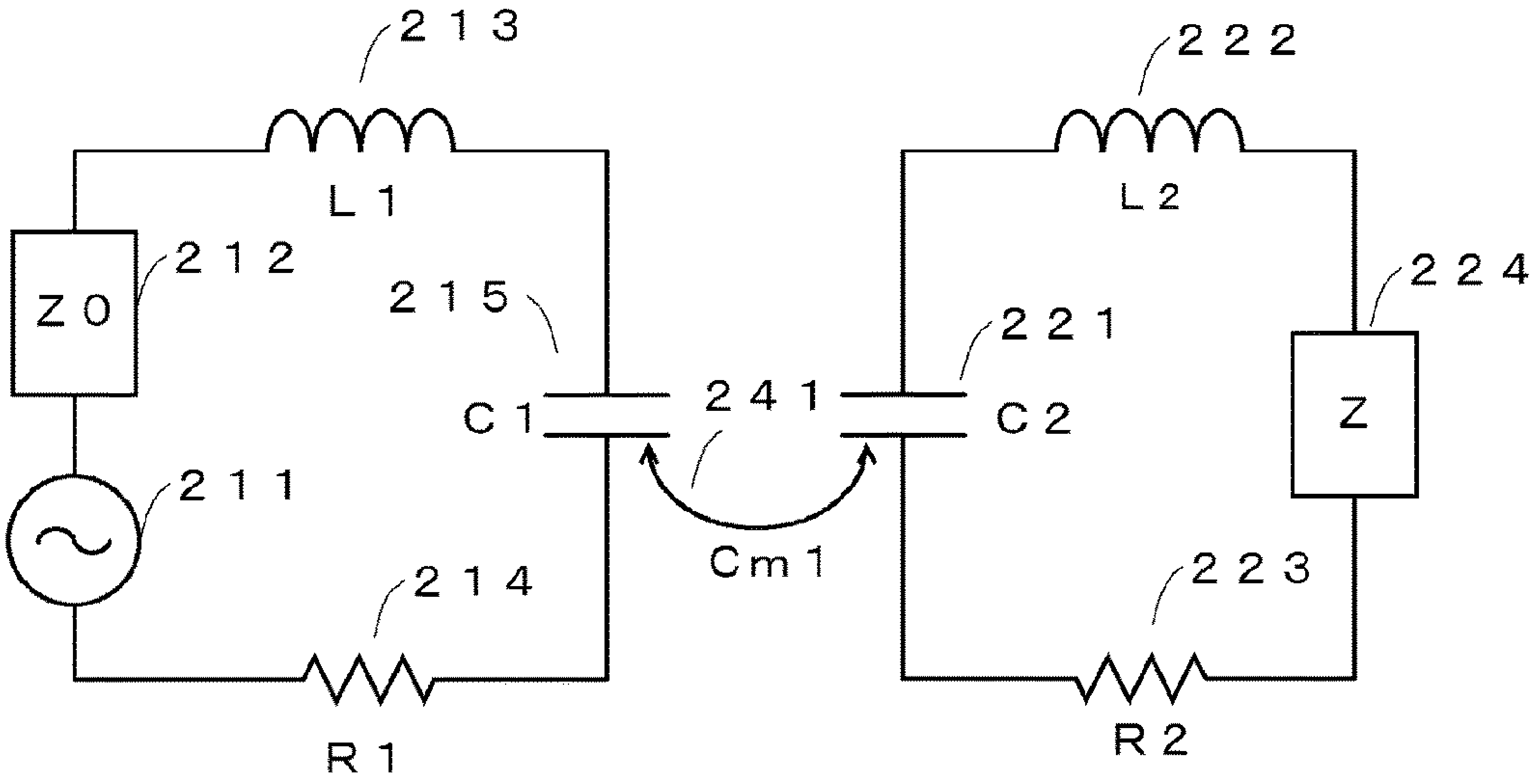
FIG.3



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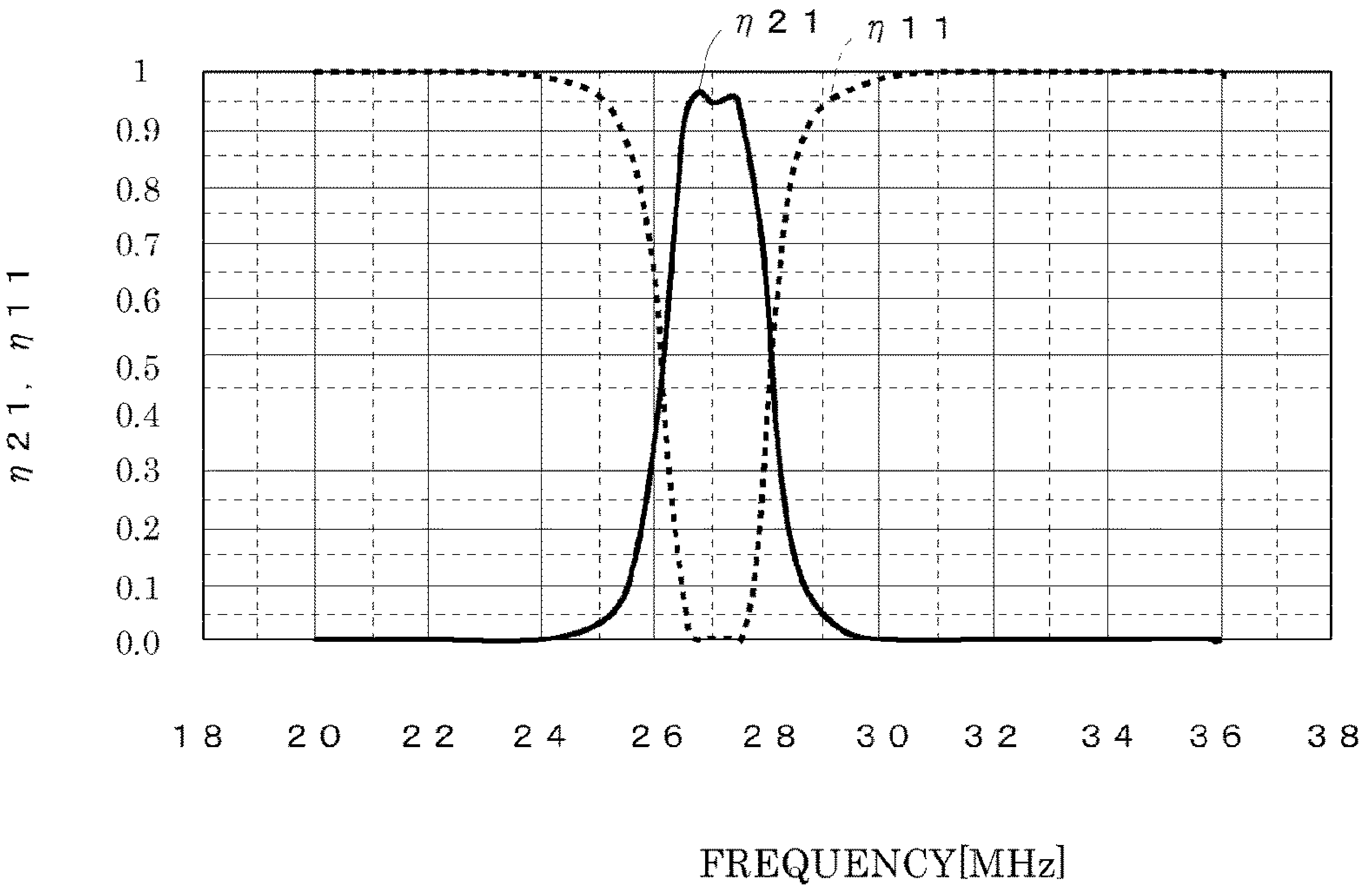
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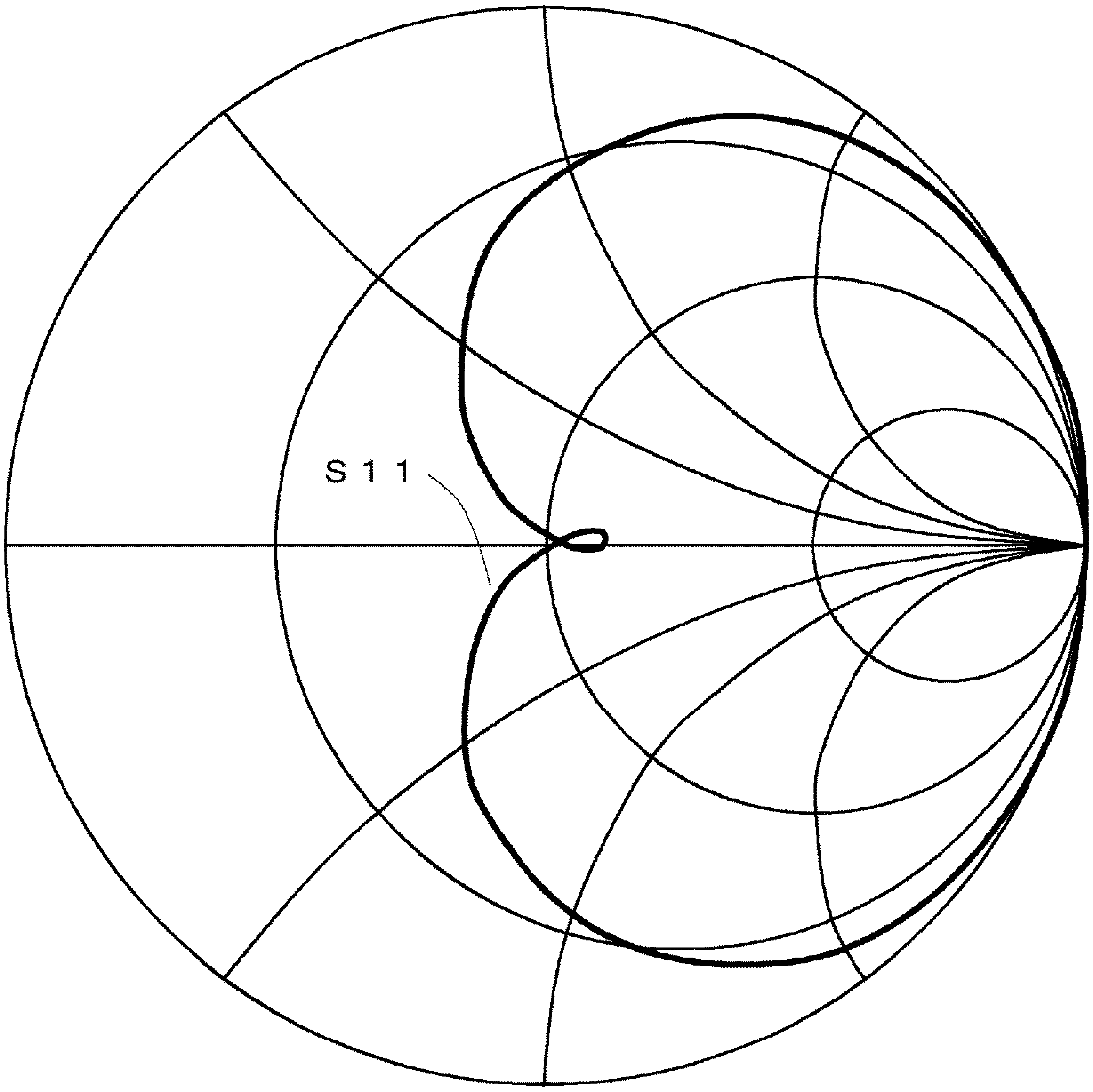
FIG.5



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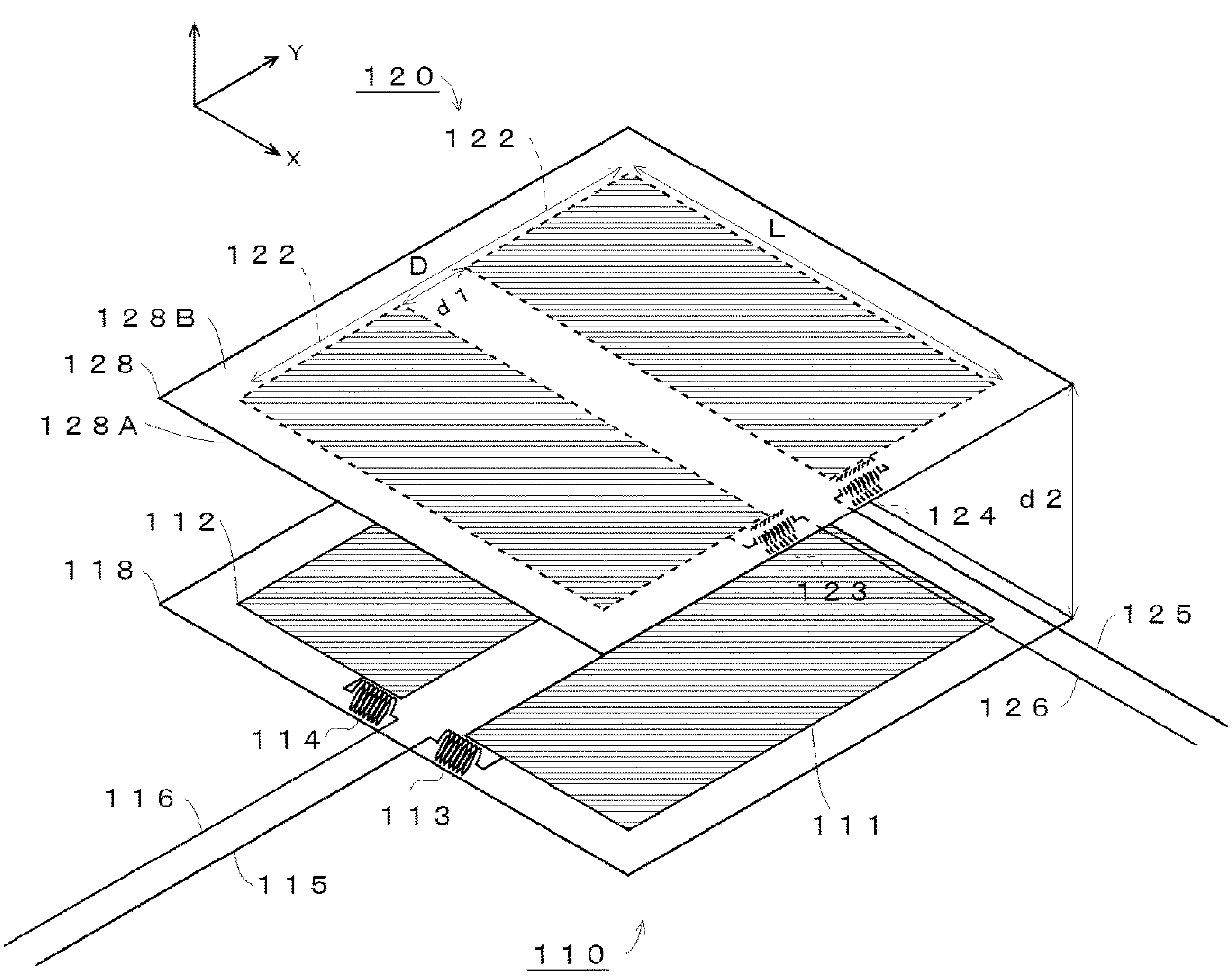
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FIG.7

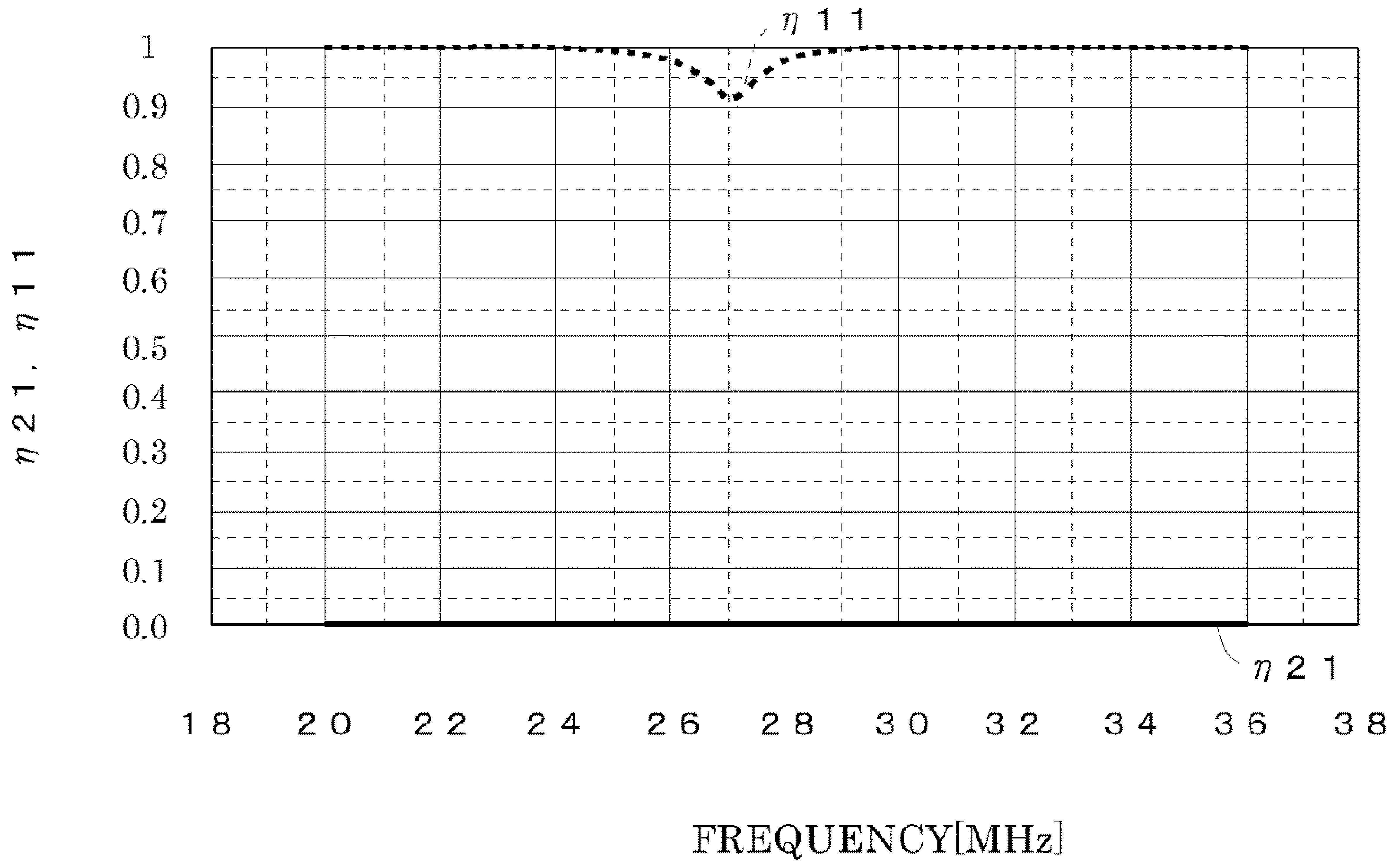
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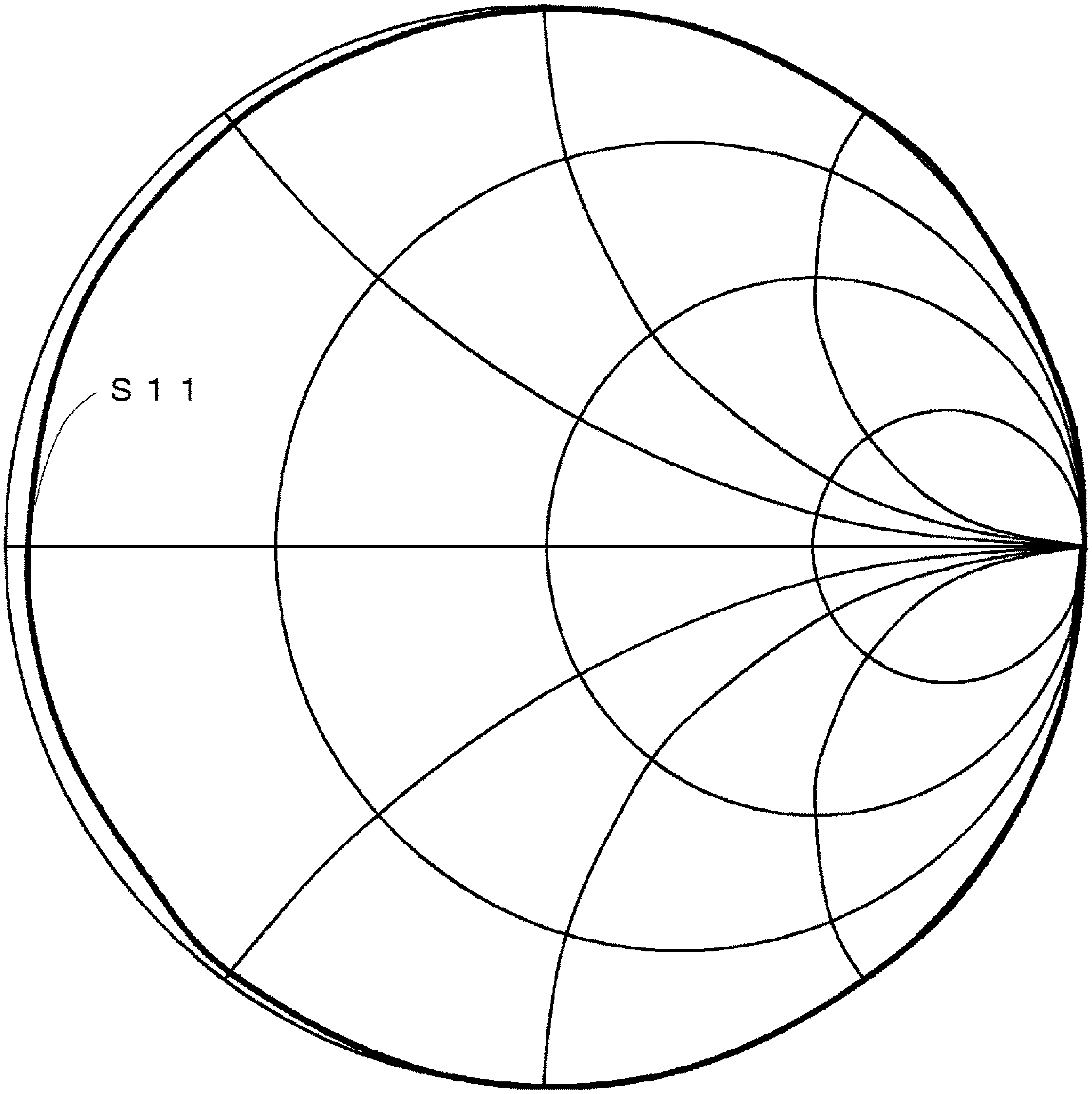
FIG.8



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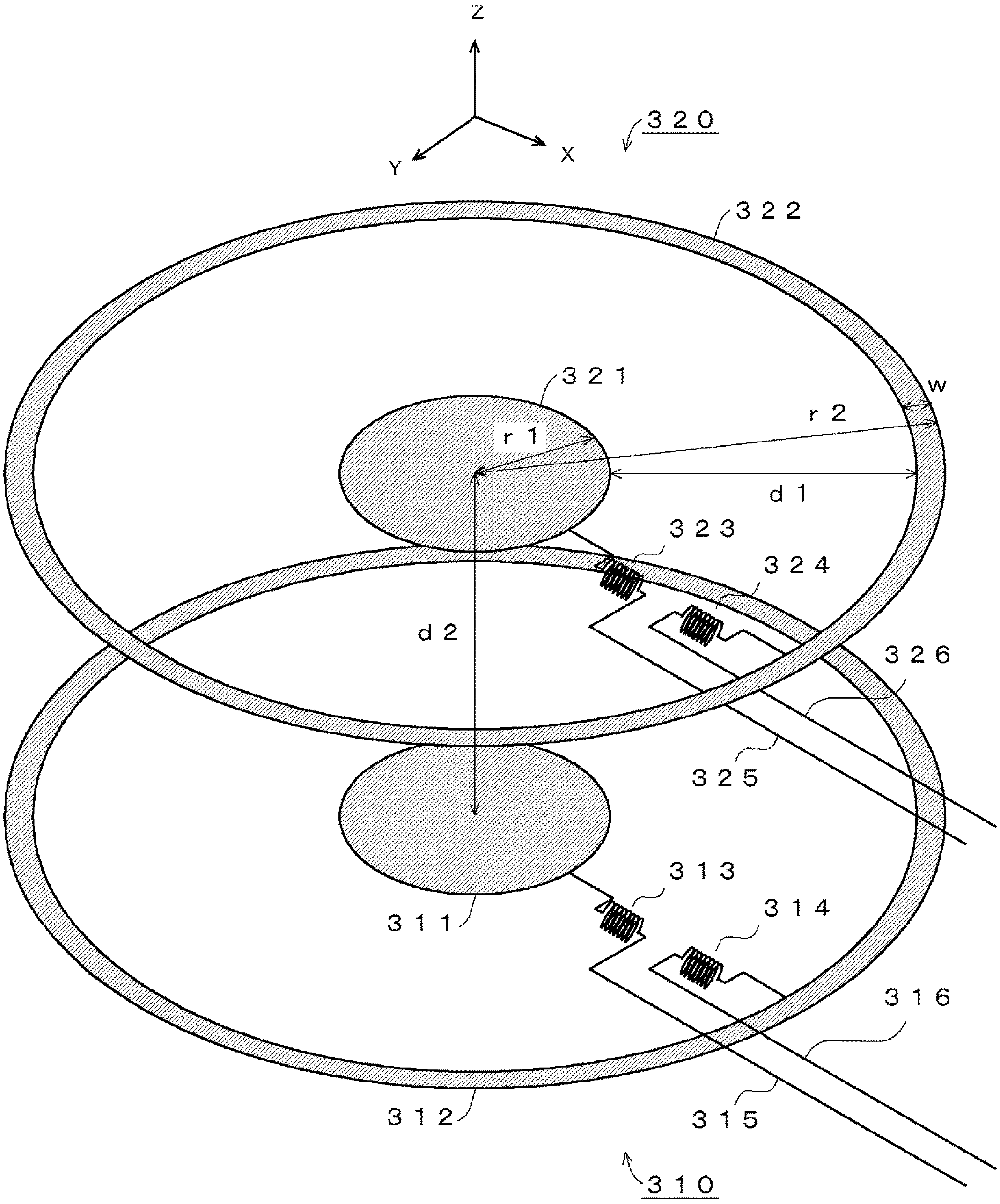
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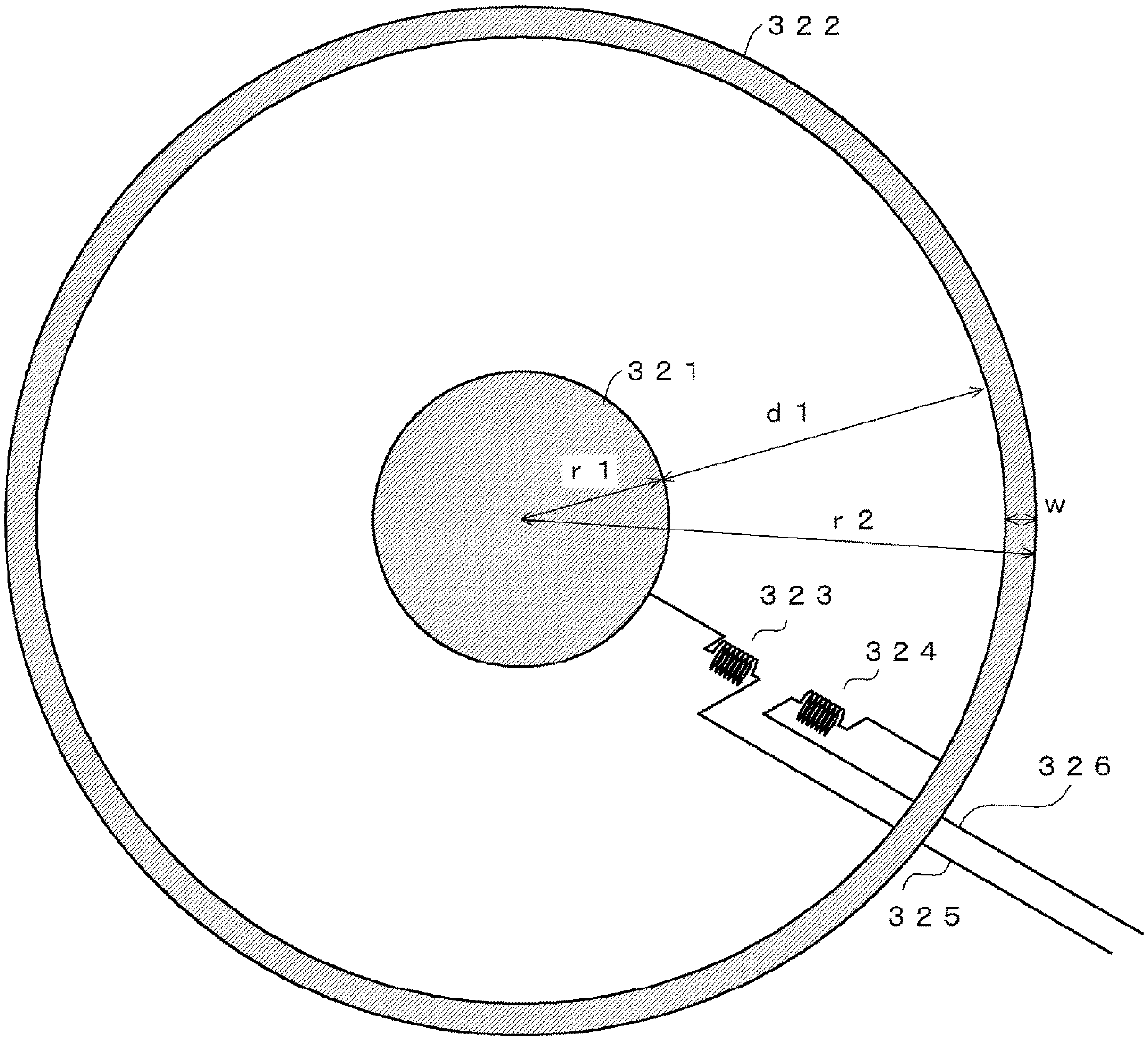
FIG.10



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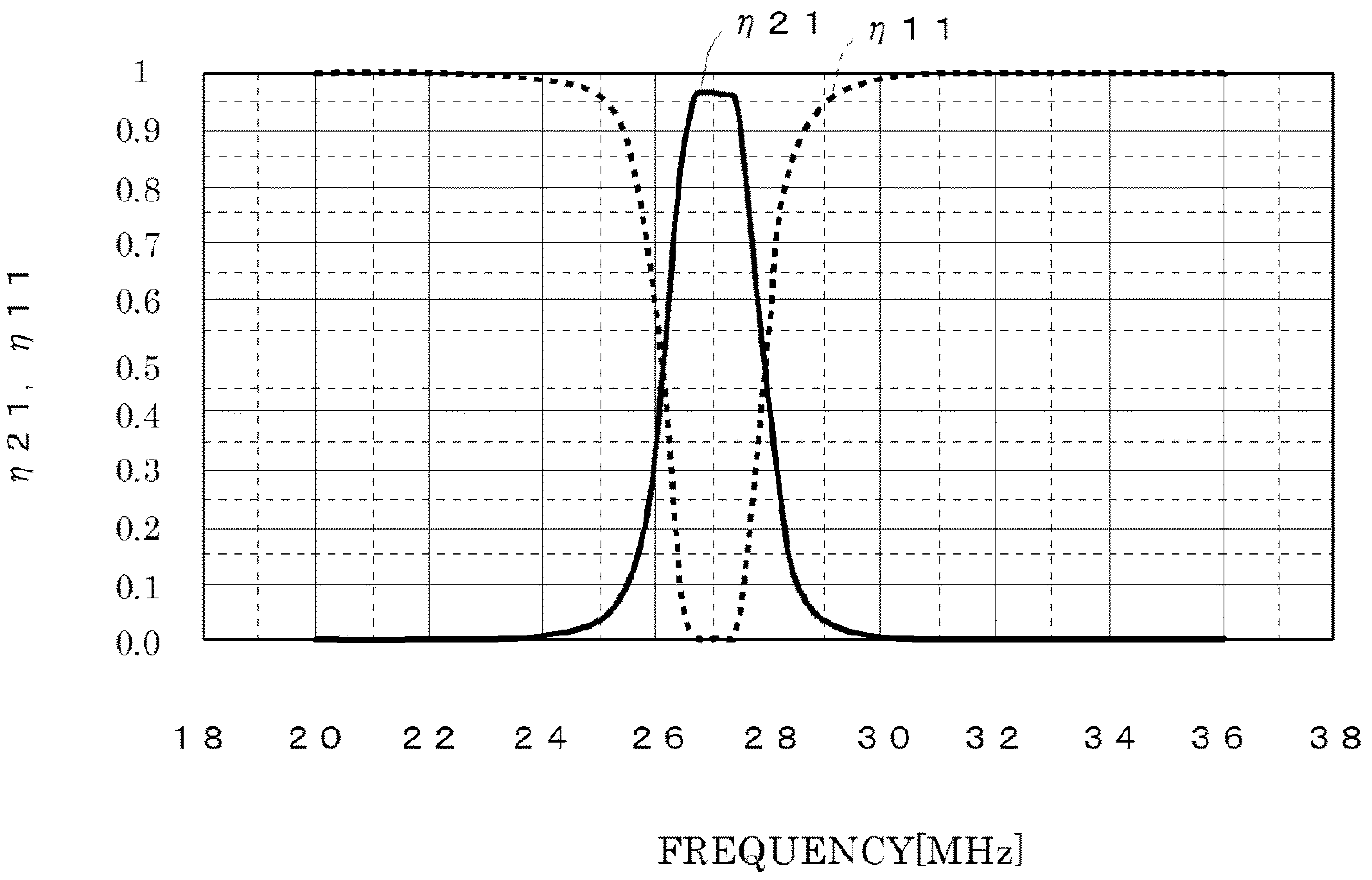
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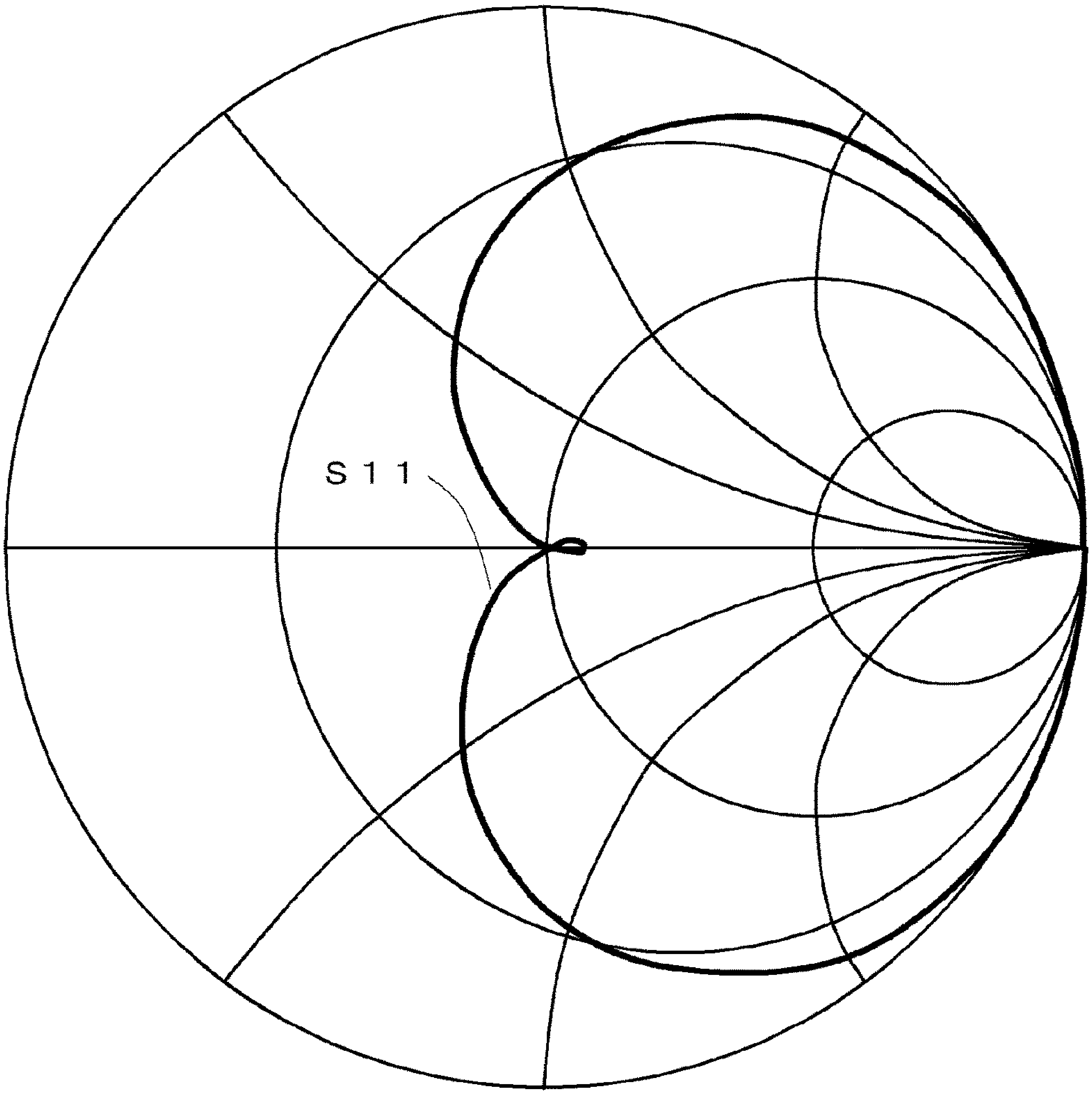
FIG.12



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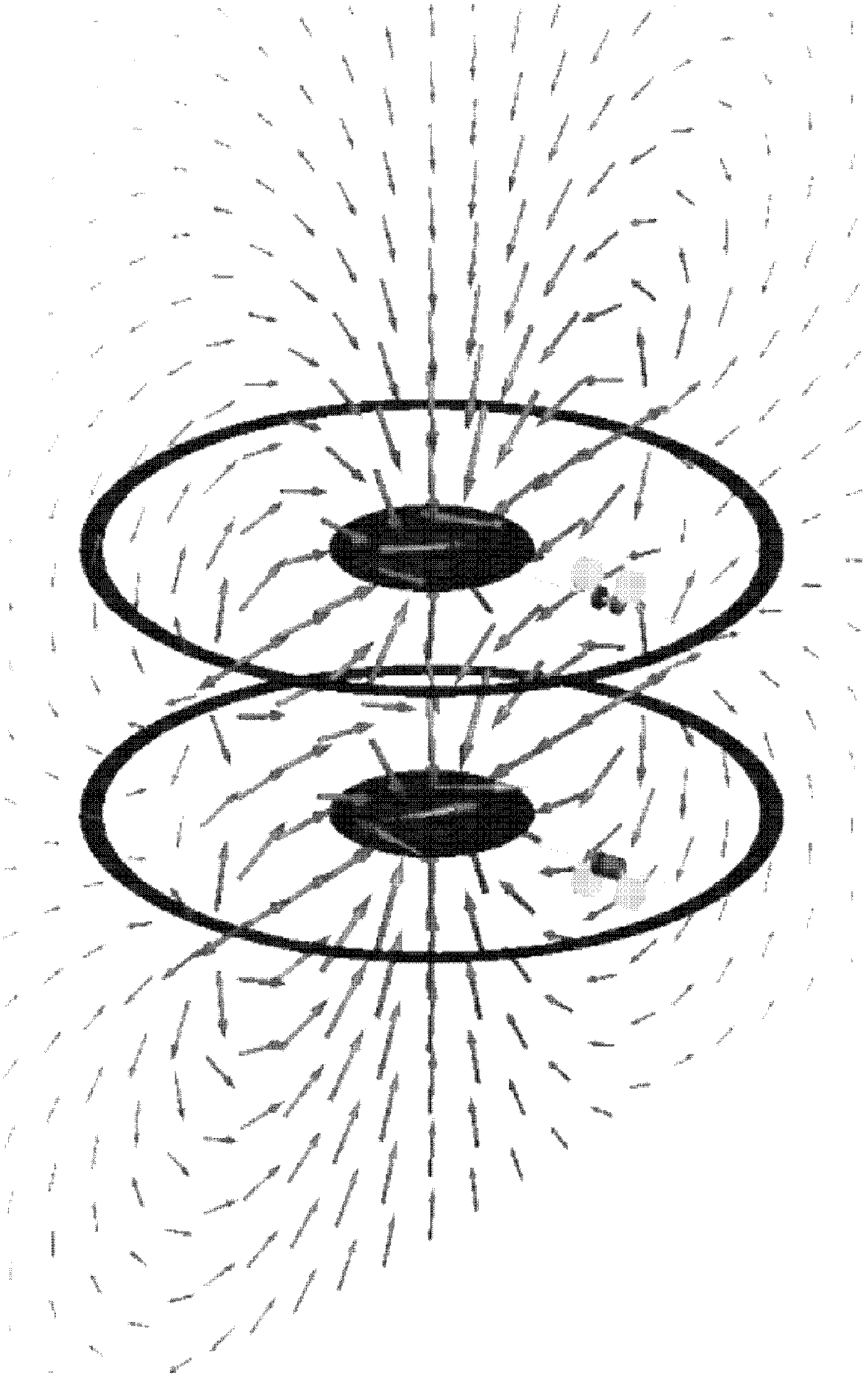

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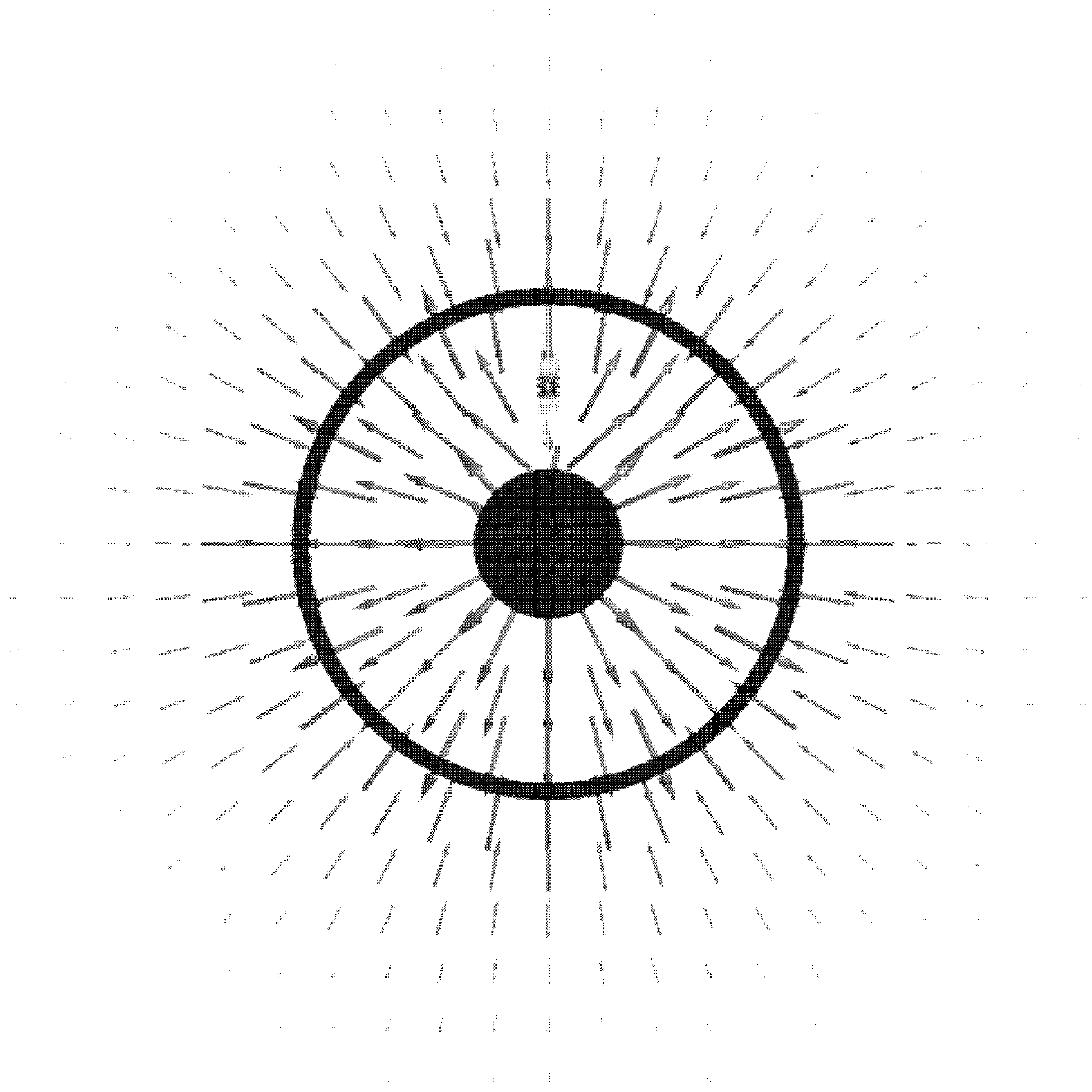
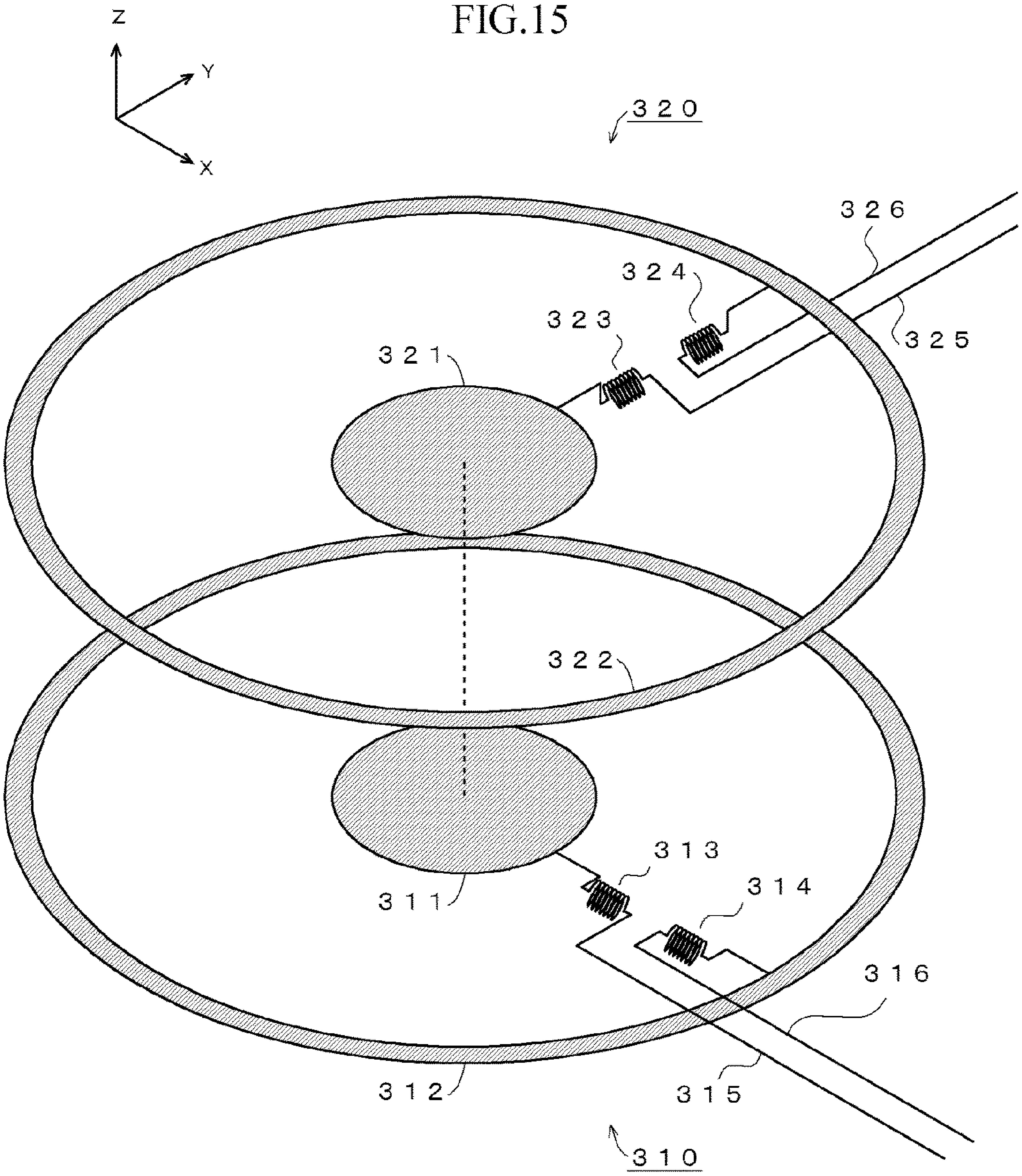


FIG.15



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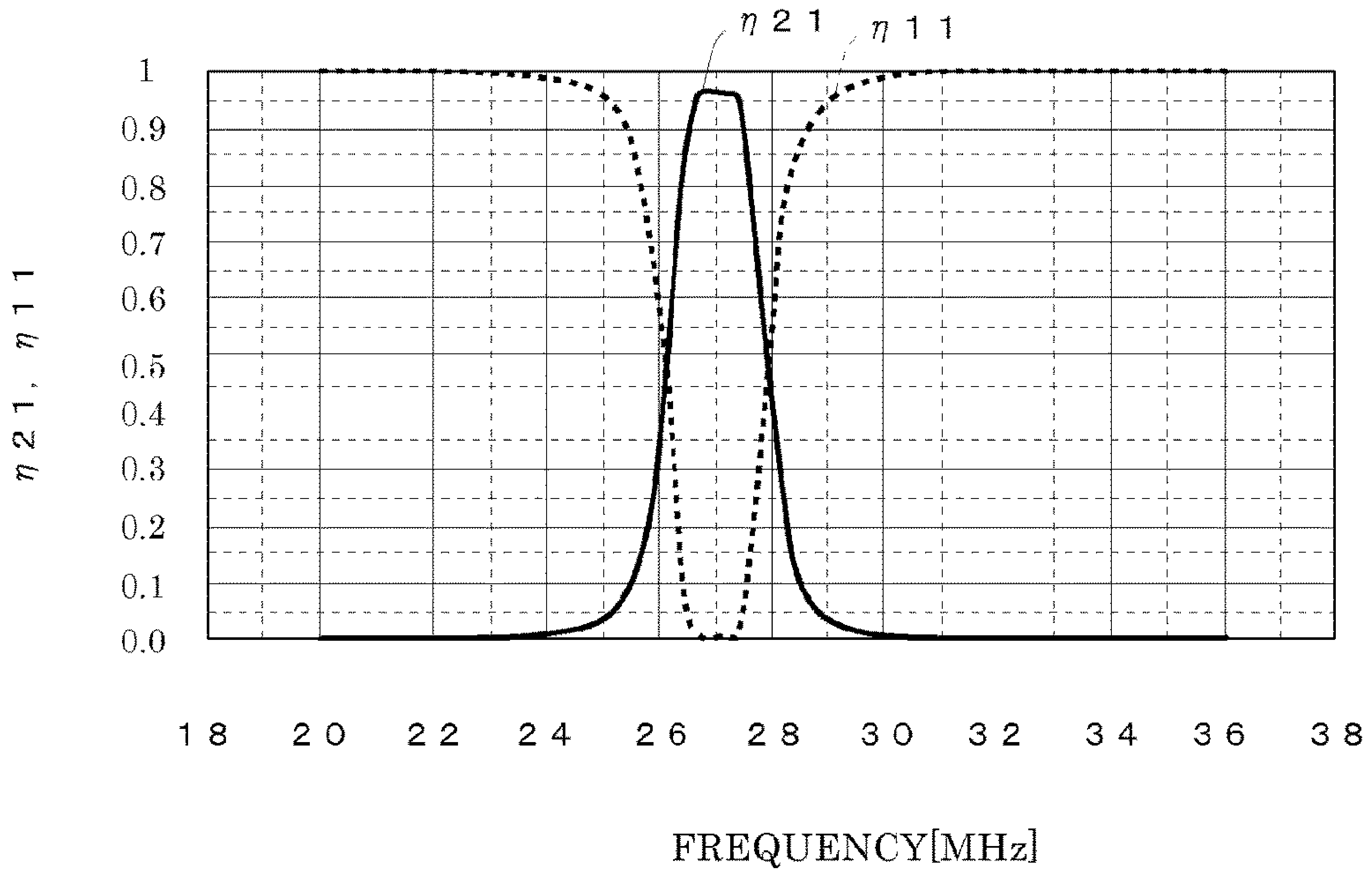
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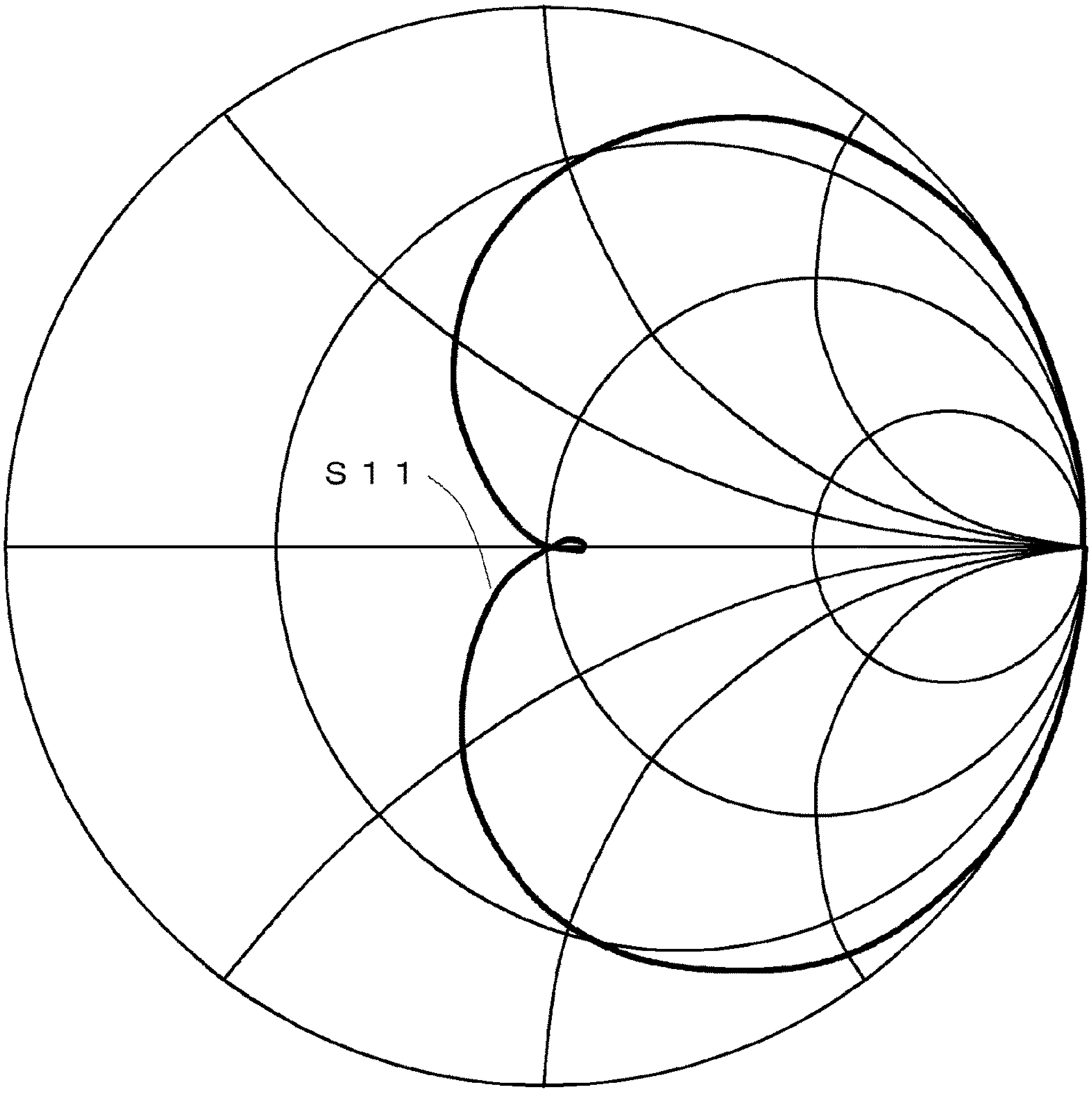
FIG.17



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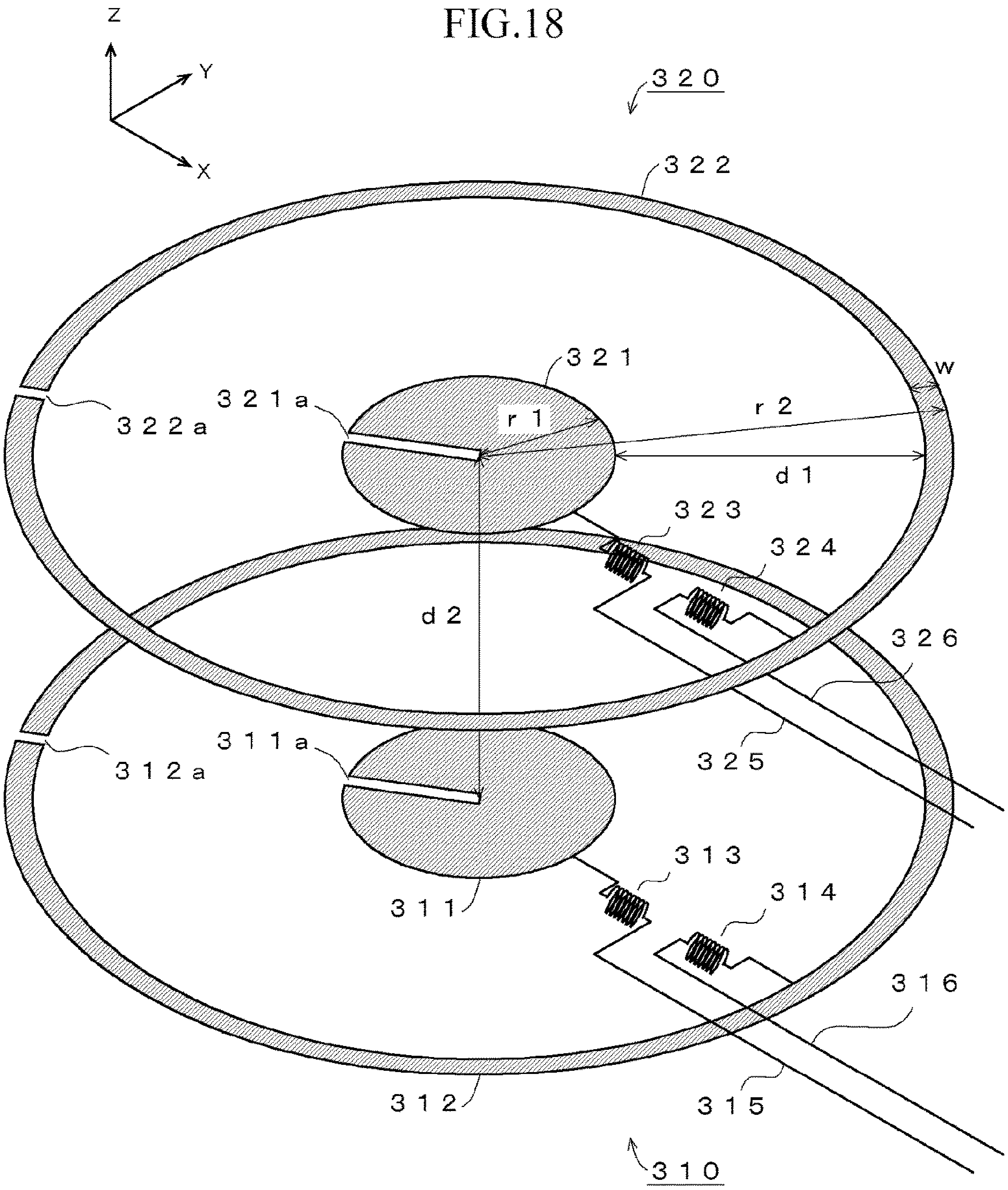
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FIG.19

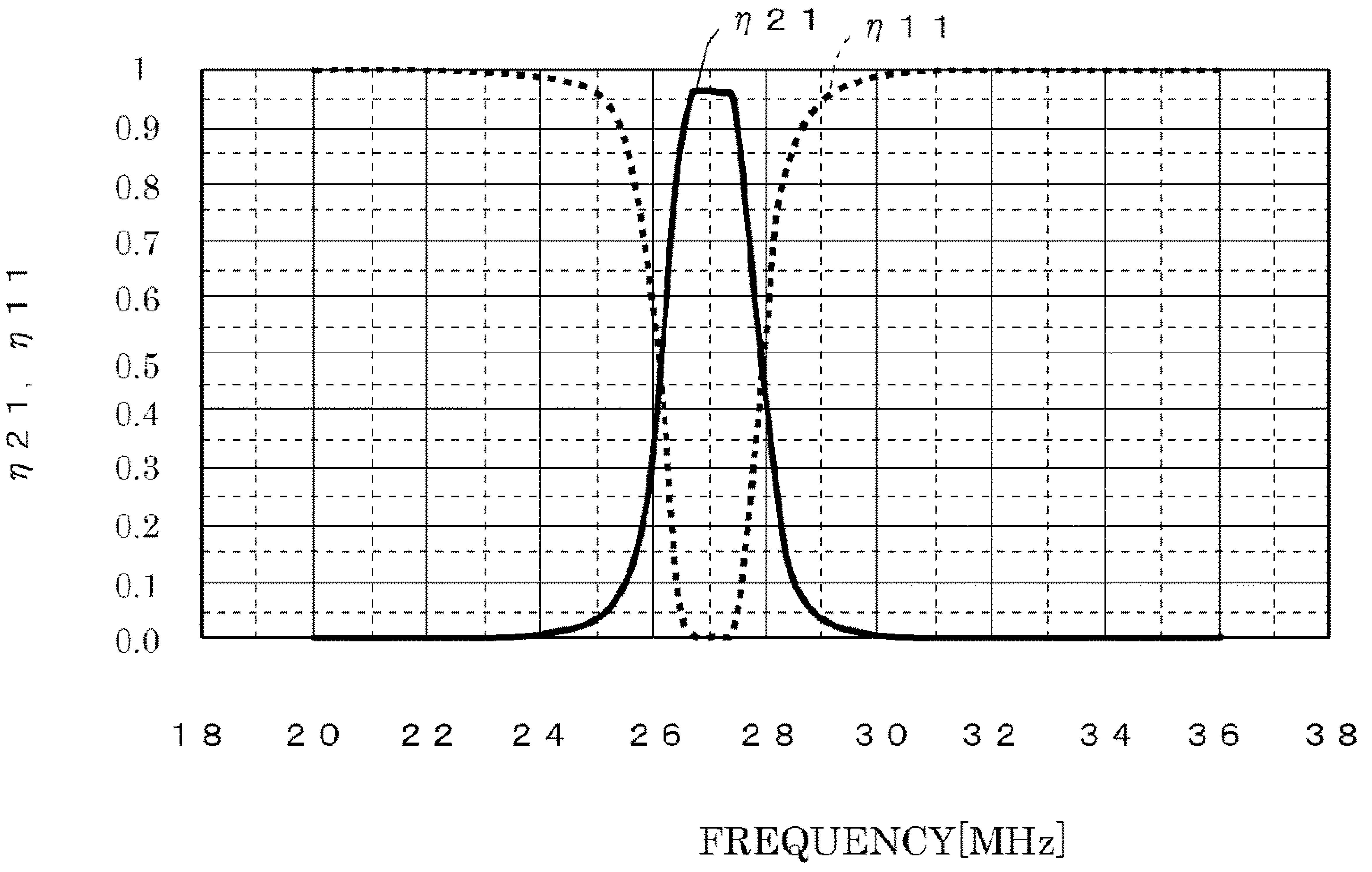
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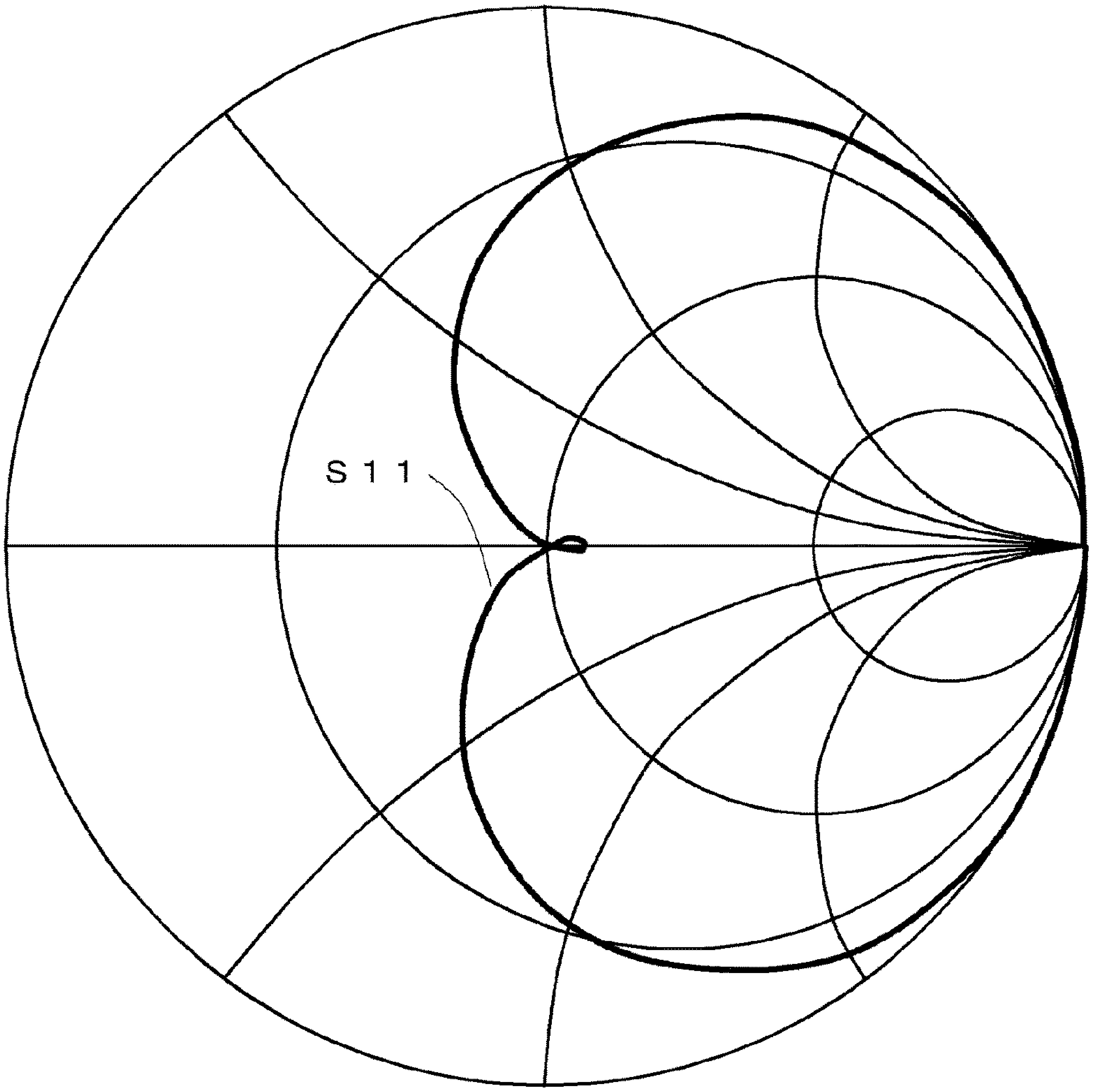
FIG.20



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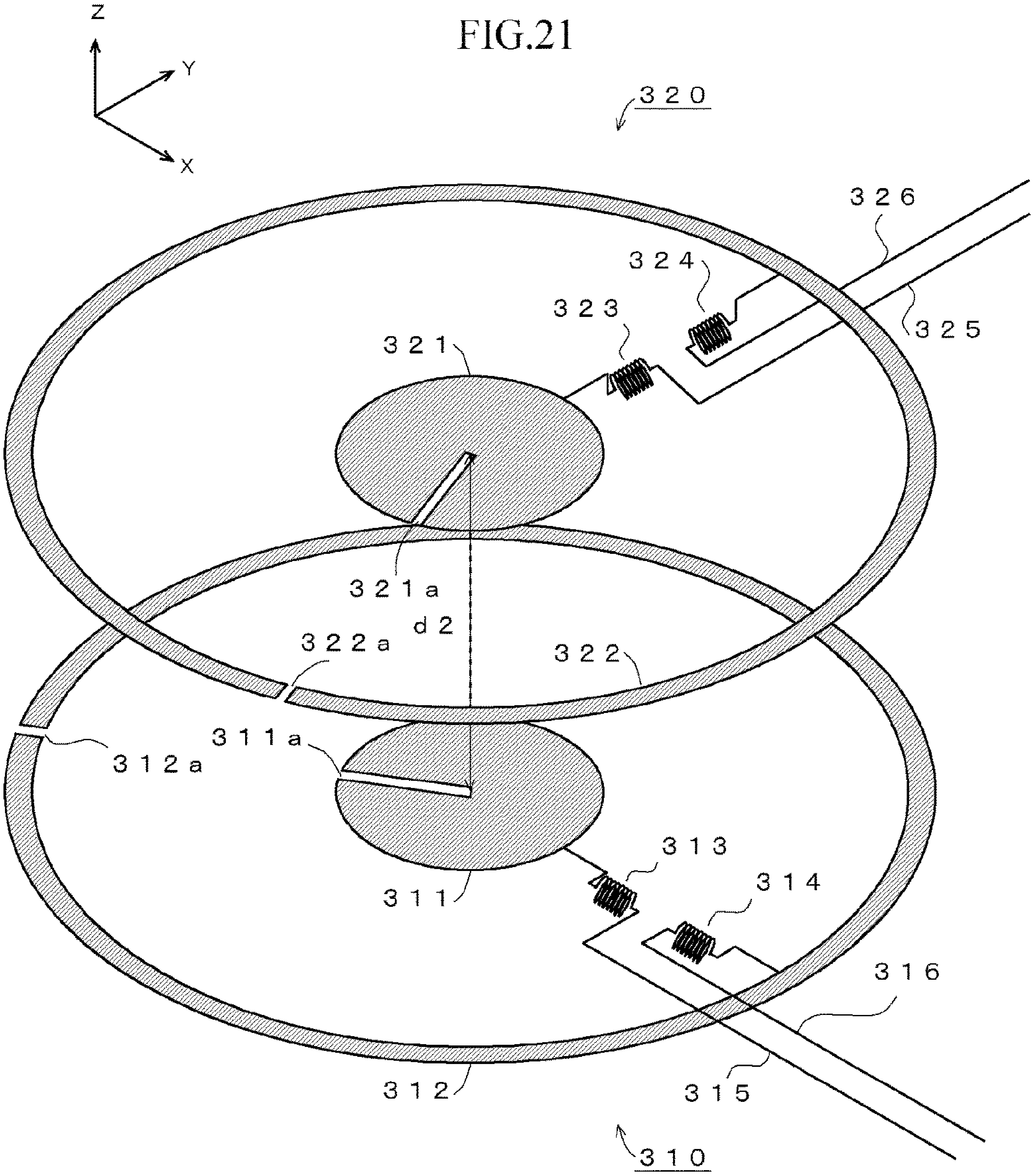
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FIG.22

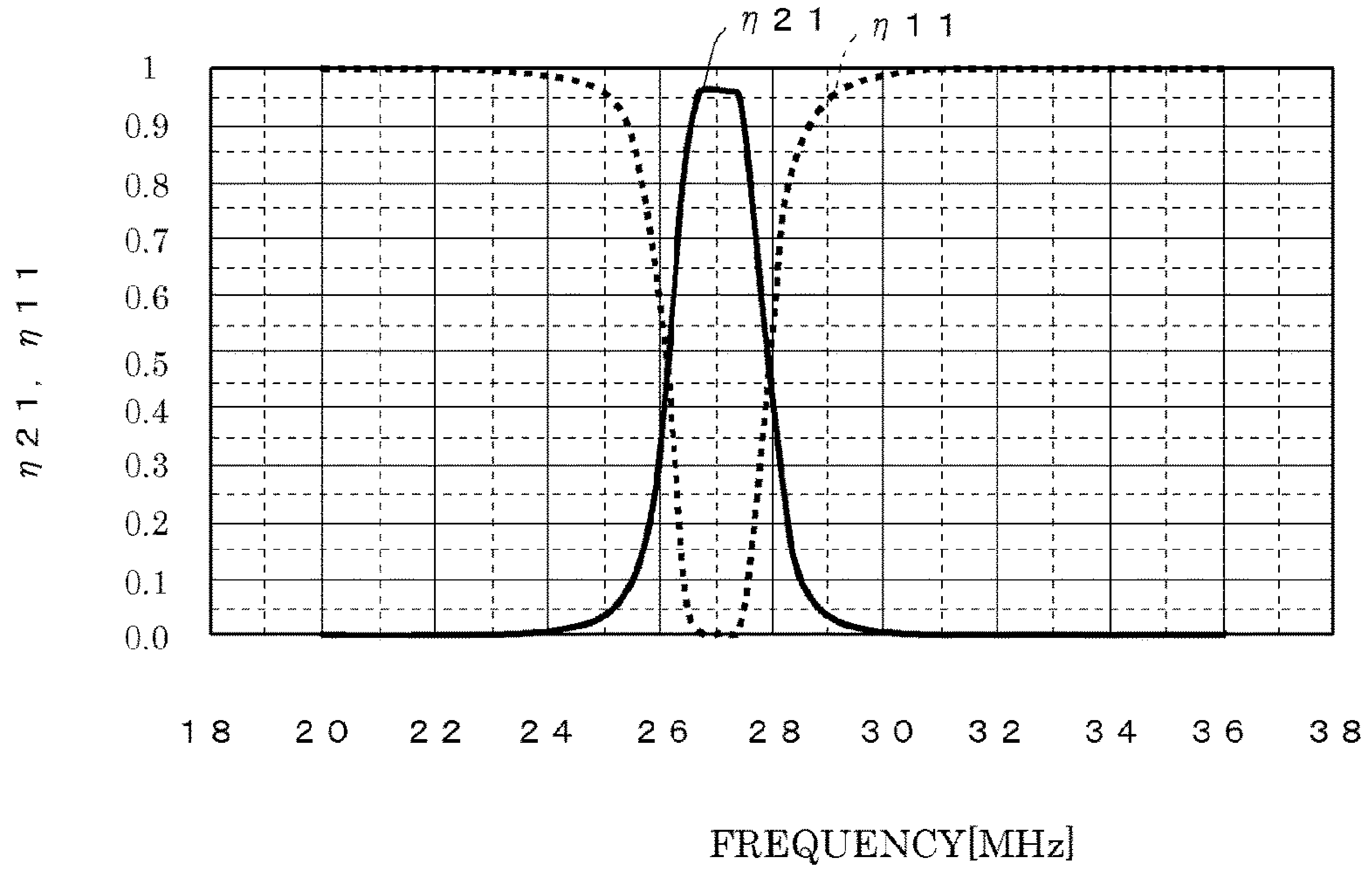
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FIG.23

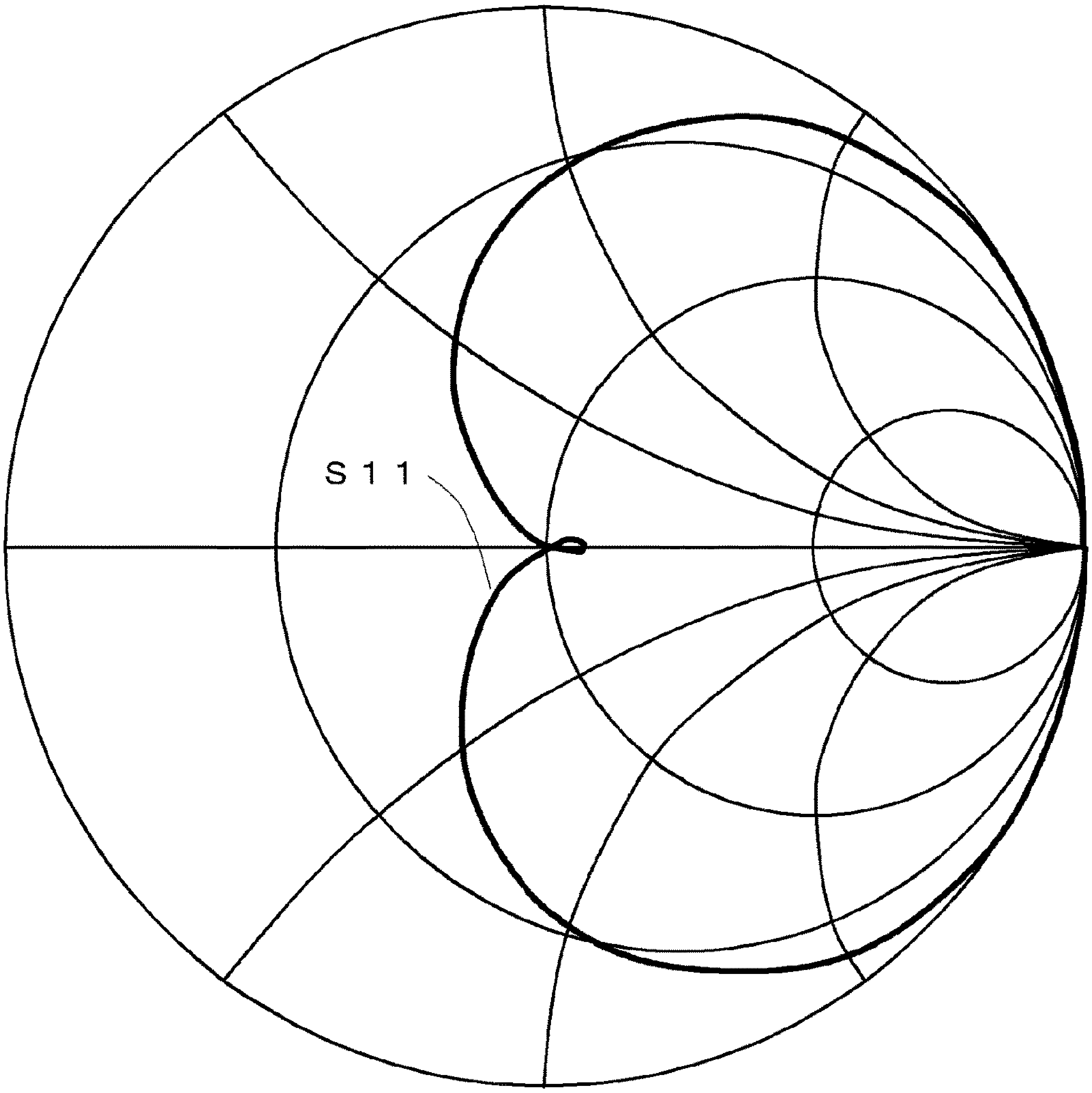

FIG.24

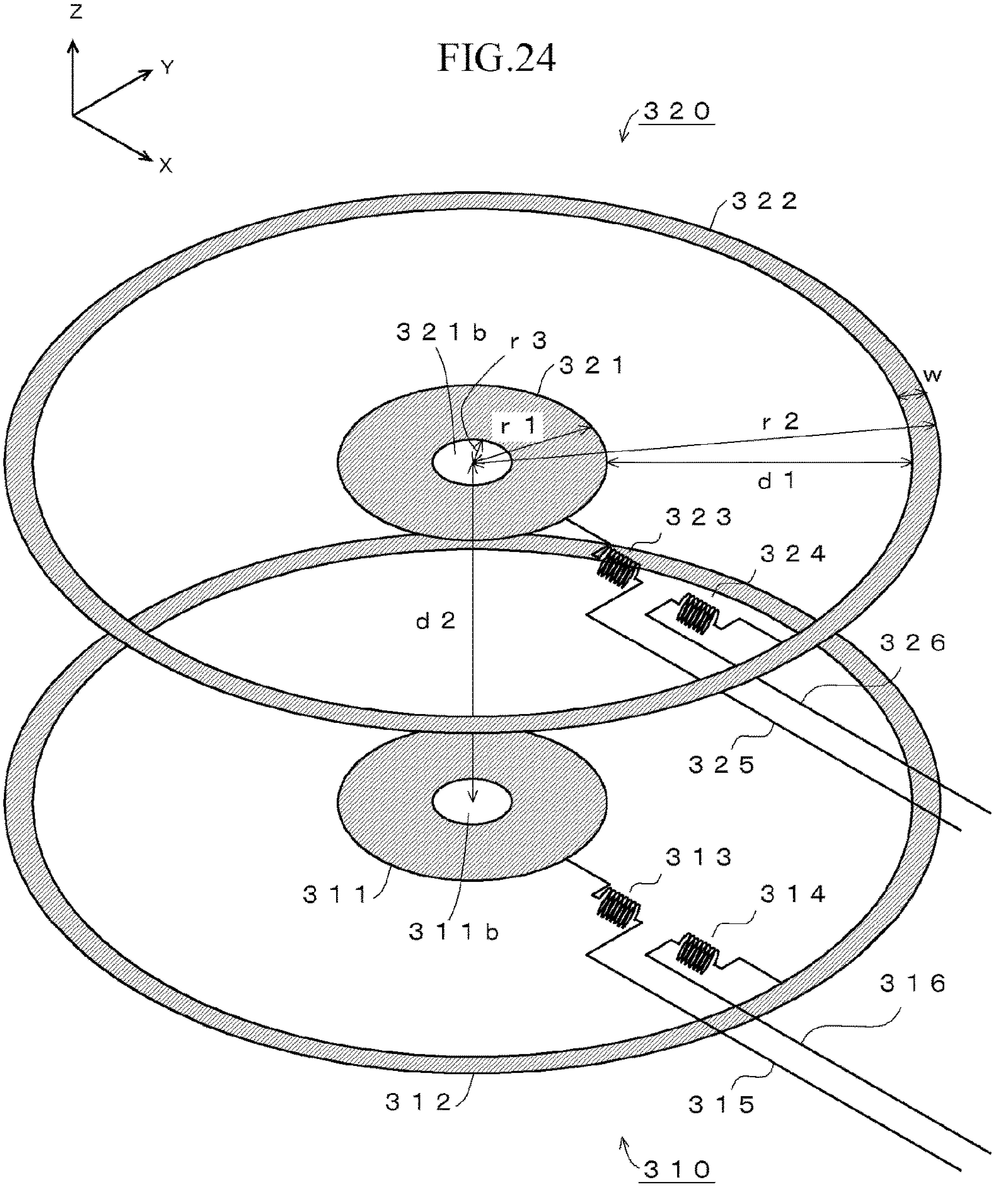
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FIG.25

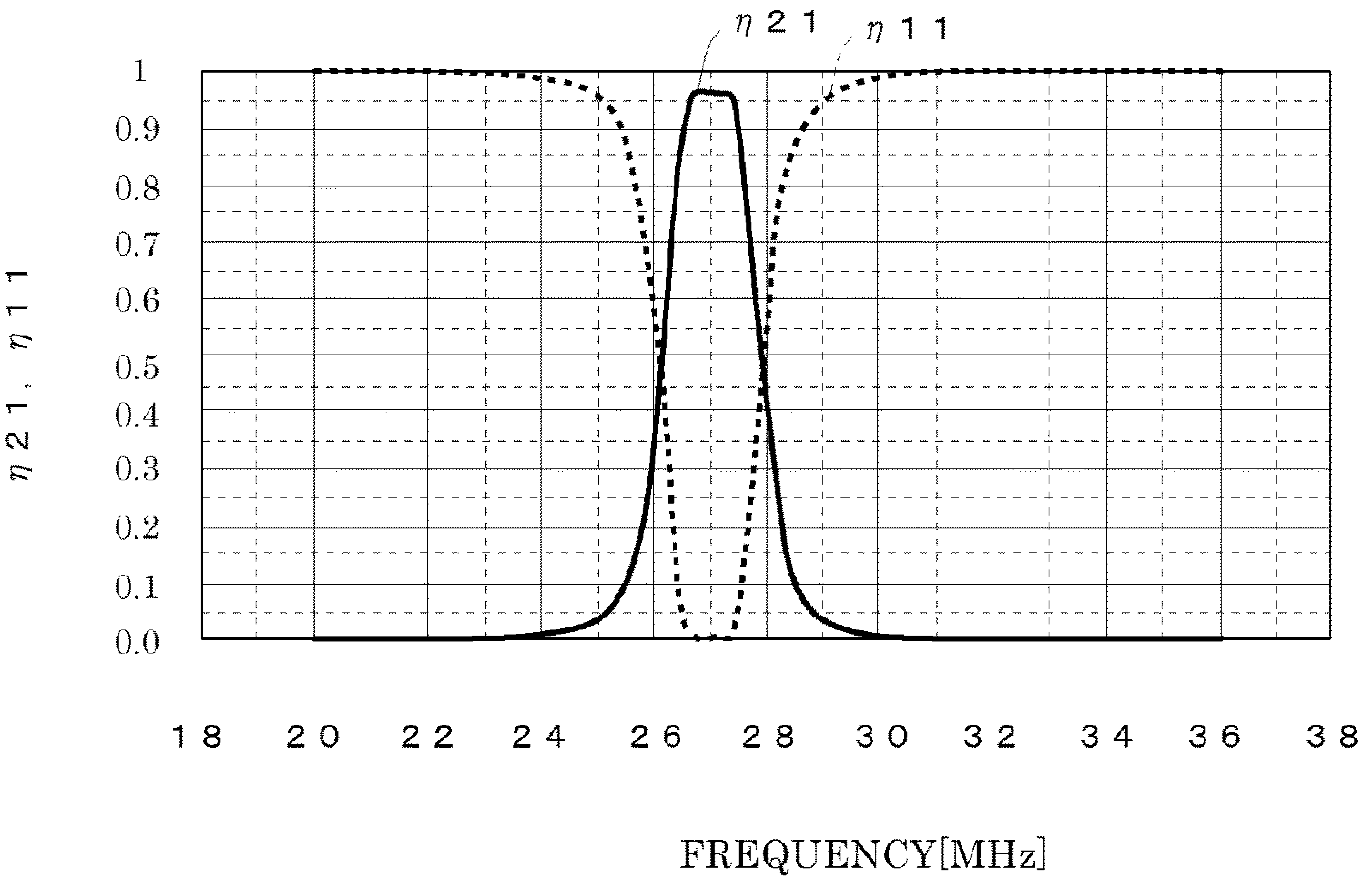

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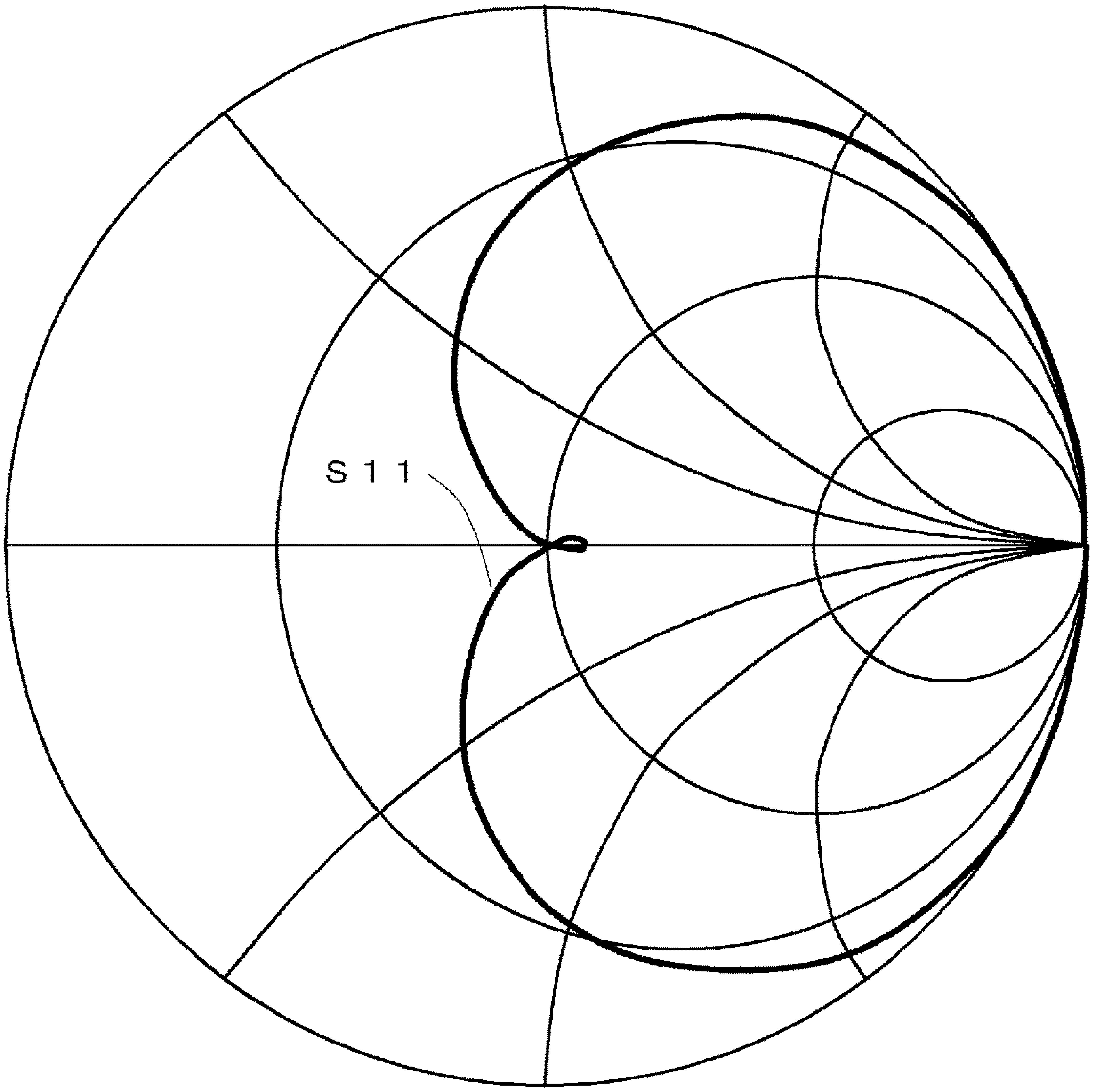
FIG.26



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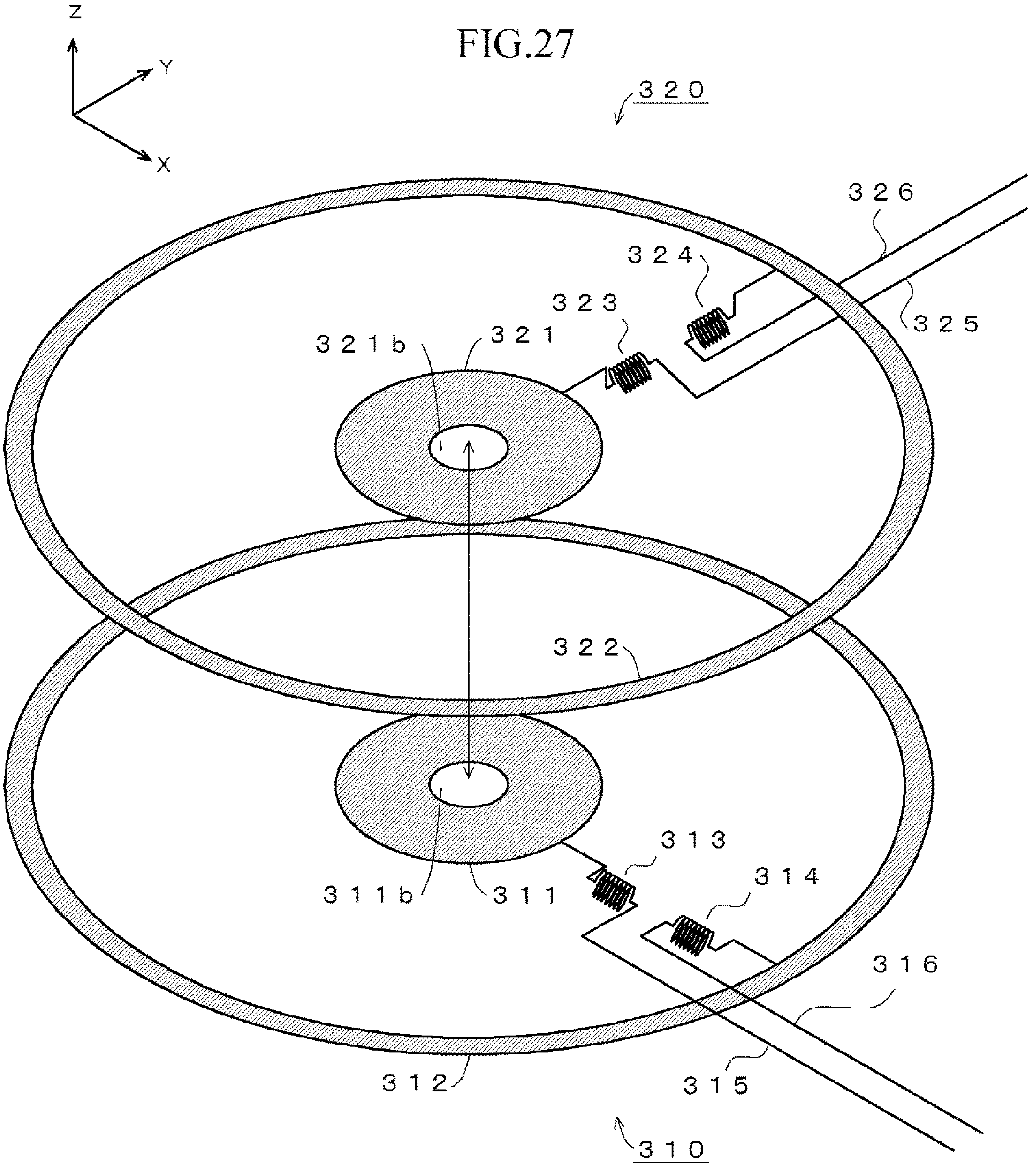
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FIG.28

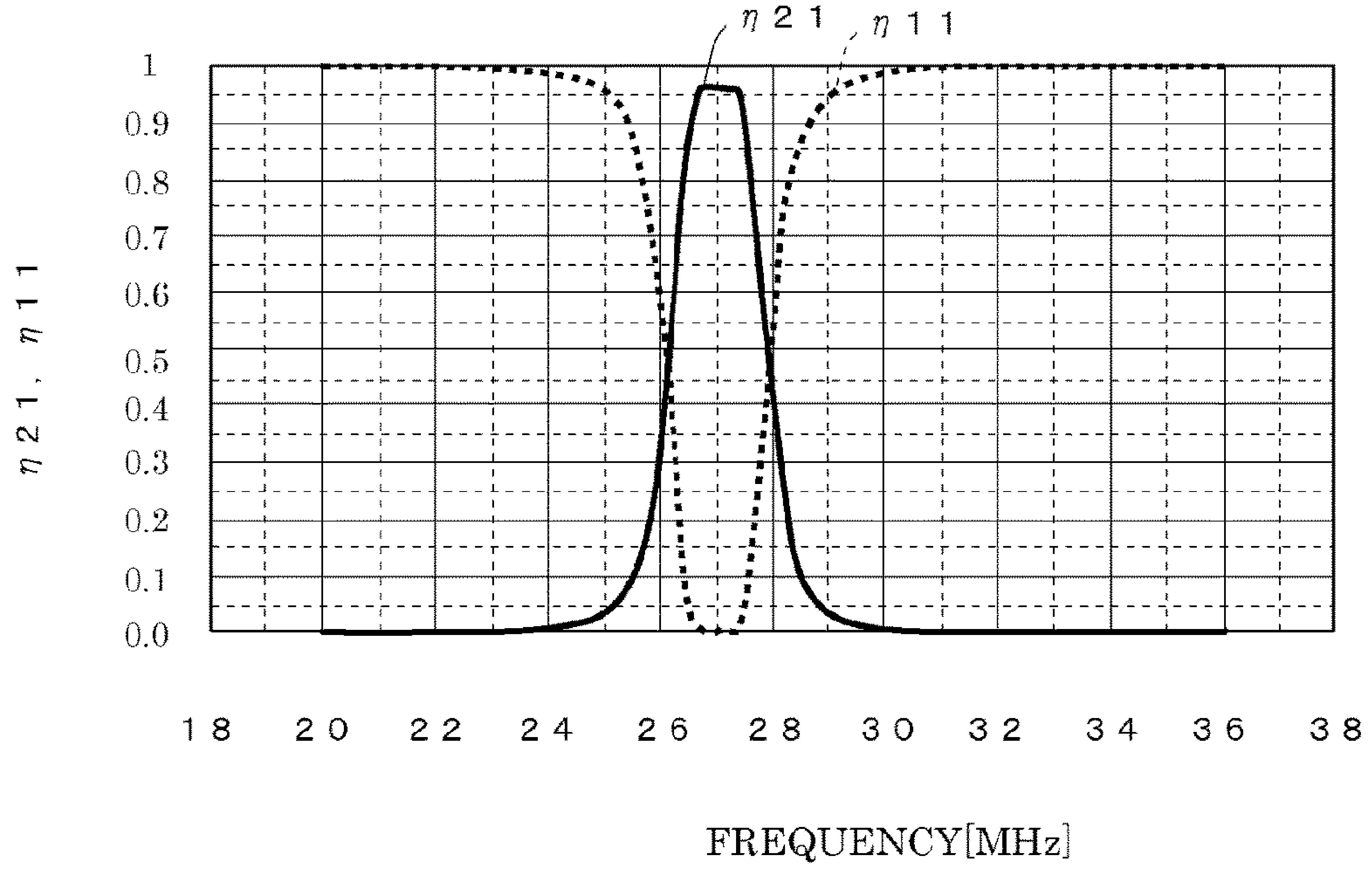
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FIG.29

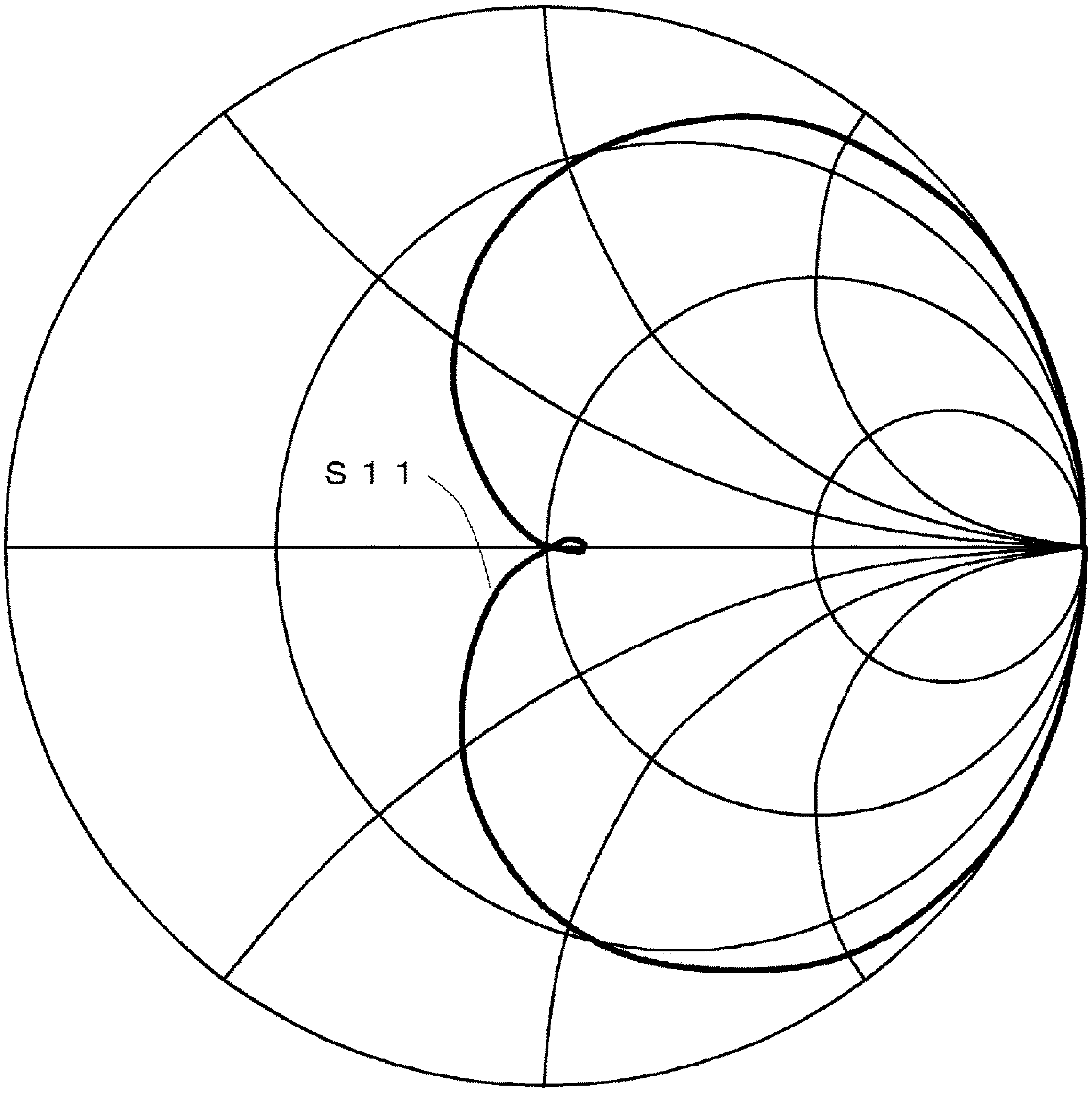
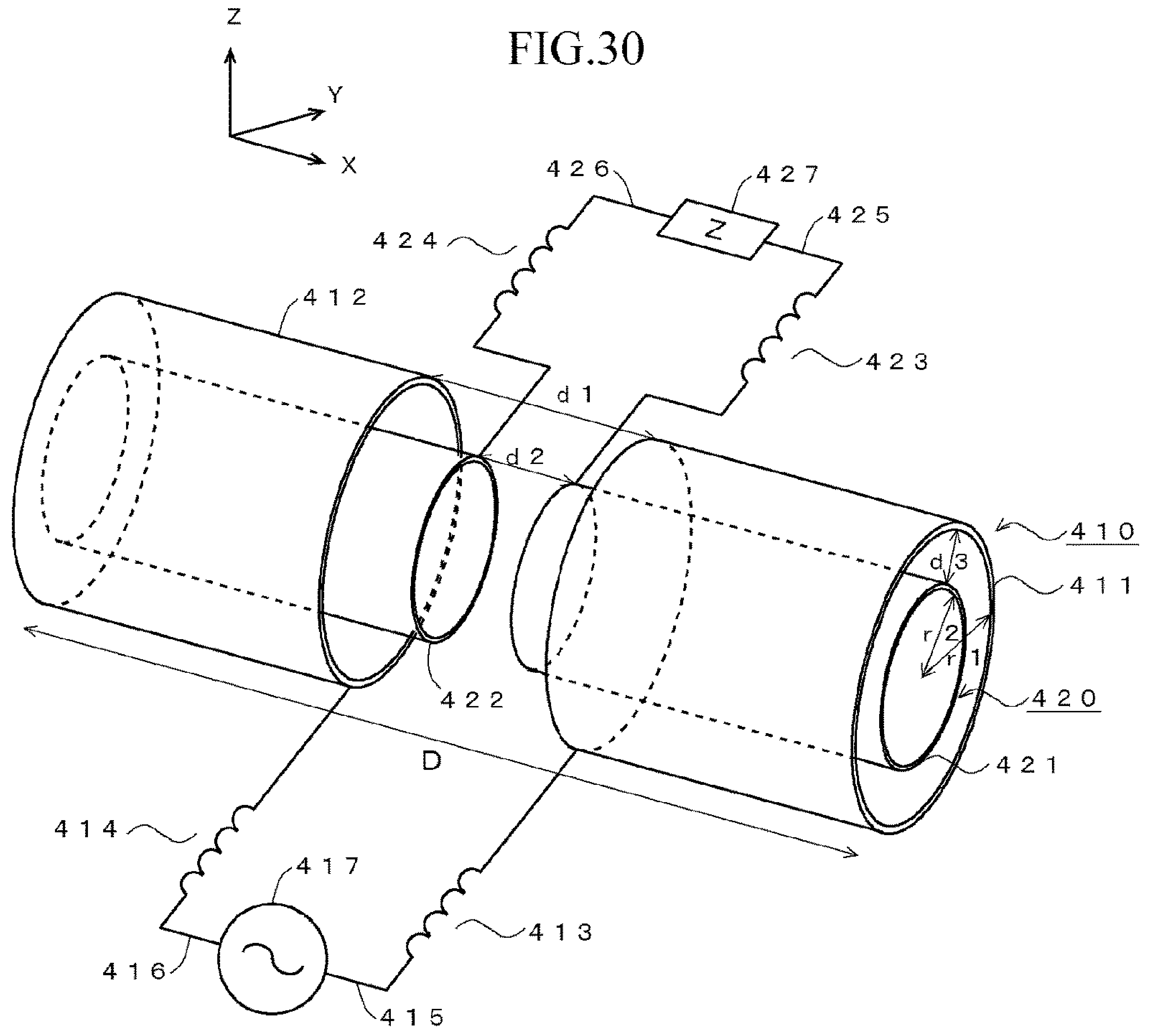


FIG.30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WIRELESS POWER TRANSMISSION SYSTEM FOR TRANSMITTING ALTERNATING-CURRENT POWER WIRELESSLY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of, and claims priority to, International Application No. PCT/JP2013/081826, filed Nov. 27, 2013 and entitled "WIRELESS POWER TRANSMISSION SYSTEM", which claims priority to Japanese Patent Application No. 2013-017774, filed Jan. 31, 2013, the disclosures of each of which are incorporated herein by reference in their entireties.

TECHNICAL FIELD

The present invention relates to a wireless power transmission system.

BACKGROUND ART

Patent Document 1 discloses a wireless power transmission device which performs transmission of power between two non-contact electric circuits by using electromagnetic induction.

PRIOR ART DOCUMENT

Patent Document

Patent Document 1: Japanese Patent Application Laid-open No. H8-340285

SUMMARY OF THE INVENTION

Problems to be Solved by the Invention

Incidentally, in the technology disclosed in Patent Document 1, power loss in a coil for transmitting power is large, and thus there is a problem that power cannot be transmitted efficiently. Further, in a second embodiment illustrated in FIG. **11**, when it is rotated about an axis of the coupler, the coil for transmitting power is displaced in position and changes in characteristics, and thus there is a problem that power cannot be transmitted efficiently.

Accordingly, it is an object of the present invention to provide a wireless power transmission system capable of transmitting power efficiently even when it is rotated.

Means for Solving the Problems

In order to solve the above problems, the present invention is characterized by a wireless power transmission system transmitting alternating-current power from a power transmission device to a power reception device, wherein the power transmission device has: a first and a second electrode which are disposed across a predetermined distance, in which a total width including the predetermined distance is $\lambda/2\pi$ or less as a near field, the first and the second electrode each having a rotationally symmetrical shape with respect to a common center axis; a first and a second connection line electrically connecting the first and the second electrode and two output terminals of an alternating-current power generating unit, respectively; and a first inductor residing between the first and the second electrode and at least one of the two output terminals of the alternating current power generating unit, and the power reception device has: a third and a fourth electrode which are disposed across a predetermined distance, in which a total width including the predetermined distance is $\lambda/2\pi$ or less as a near field, the third and the fourth electrode each having a rotationally symmetrical shape with respect to a common center axis; a third and a fourth connection line electrically connecting the third and the fourth electrode and two input terminals of a load, respectively; and a second inductor residing between the third and the fourth electrode and at least one of the two input terminals of the load, wherein the electrodes of the power transmission device and the power reception device are disposed to oppose each other across a distance of $\lambda/2\pi$ or less as a near field, and a resonance frequency of a coupler constituted of the first and the second electrode and the first inductor and a resonance frequency of a coupler constituted of the third and the fourth electrode and the second inductor are set to be substantially equal.

With such a structure, power can be transmitted efficiently even when it is rotated.

Further, one aspect of the present invention is characterized in that the first electrode has a platy polygonal or circular shape, and the second electrode has a platy polygonal or circular annular shape disposed to surround the first electrode and is disposed on a same plane to have a center axis corresponding to that of the first electrode; the third electrode has a platy polygonal or circular shape, and the fourth electrode has a platy polygonal or circular annular shape disposed to surround the third electrode and is disposed on a same plane to have a center axis corresponding to that of the third electrode; and the first and the second electrode and the third and the fourth electrode are disposed to oppose each other across a distance of $\lambda/2\pi$ or less as a near field.

With such a structure, even when it is rotated around an axis, decrease in transmission efficiency can be prevented reliably.

Further, one aspect of the present invention is characterized in that at least one of the first to the fourth electrode has a cutout in a radial direction.

With such a structure, a cutout for attaching an electrode can be provided without leading to deterioration in characteristics.

Further, one aspect of the present invention is characterized in that at least one of the first electrode and the third electrode has an annular shape.

With such a structure, a through hole for attaching an electrode can be provided without leading to deterioration in characteristics.

Further, one aspect of the present invention is characterized in that at least one of the first to the fourth electrode has a three-dimensional structure extending in an axial direction.

With such a structure, a member having a three-dimensional shape can be used as an electrode.

Further, one aspect of the present invention is characterized in that the first and the second electrode have a polygonal or circular cylindrical shape and the third and the fourth electrode have a polygonal or circular cylindrical shape disposed to surround the first and the second electrode, respectively, and are disposed to have a center axis corresponding to that of the first and the second electrode, and

the first and the third electrode and the second and the fourth electrode are disposed to oppose each other across a distance of $\lambda/2\pi$ or less as a near field.

With such a structure, even when it is rotated around an axis, decrease in transmission efficiency can be prevented reliably.

Effect of the Invention

According to the present invention, it is possible to provide a wireless power transmission system capable of transmitting power efficiently even when it is rotated.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a view illustrating a detailed structural example of a power transmission device constituting a wireless power transmission system utilizing series resonance.

FIG. **2** is a view illustrating a structural example of the wireless power transmission system utilizing series resonance.

FIG. **3** is an equivalent circuit of the wireless power transmission system illustrated in FIG. **2**.

FIG. **4** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **2**.

FIG. **5** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **2**.

FIG. **6** is a view illustrating a state of the case where a power reception coupler illustrated in FIG. **2** is rotated 90 degrees.

FIG. **7** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **6**.

FIG. **8** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **6**.

FIG. **9** is a perspective view illustrating a structural example of an embodiment of the present invention.

FIG. **10** is a plan view seeing the embodiment illustrated in FIG. **9** from a Z direction.

FIG. **11** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **9**.

FIG. **12** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **9**.

FIG. **13** is a diagram illustrating an electric field distribution of the embodiment illustrated in FIG. **9**

FIG. **14** is a diagram illustrating an electric field distribution of the embodiment illustrated in FIG. **10**.

FIG. **15** is a view illustrating a state of the case where a power reception coupler illustrated in FIG. **9** is rotated 90 degrees counterclockwise.

FIG. **16** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **15**.

FIG. **17** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **15**.

FIG. **18** is a view illustrating an example of a variant embodiment of the present invention.

FIG. **19** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **18**.

FIG. **20** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **18**.

FIG. **21** is a view illustrating a state of the case where a power reception coupler illustrated in FIG. **18** is rotated 90 degrees counterclockwise.

FIG. **22** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **21**.

FIG. **23** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **21**.

FIG. **24** is a view illustrating an example of another variant embodiment of the present invention.

FIG. **25** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **24**.

FIG. **26** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **24**.

FIG. **27** is a view illustrating a state of the case where a power reception coupler illustrated in FIG. **24** is rotated 90 degrees counterclockwise.

FIG. **28** is a diagram illustrating frequency characteristics of transmission efficiency and reflection loss of the wireless power transmission system illustrated in FIG. **27**.

FIG. **29** is a diagram illustrating a smith chart of impedance of a power transmission coupler illustrated in FIG. **27**.

FIG. **30** is a view illustrating an example of another variant embodiment of the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

Next, embodiments of the present invention will be described.

(A) Description of a Wireless Transmission System Utilizing Series Resonance

Hereinafter, a wireless power transmission system utilizing series resonance will be described, and thereafter embodiments of the present invention will be described.

FIG. **1** illustrates a detailed structural example of a power transmission coupler constituting a wireless power transmission system utilizing series resonance. As illustrated in this view, in the wireless power transmission system utilizing series resonance, a power transmission coupler **110** is formed by disposing electrodes **111**, **112** constituted of a conductive member having a rectangular shape on a front surface **118**A of a circuit board **118** constituted of an insulating member (dielectric substrate) having a rectangular plate shape. On a rear surface **118**B of the circuit board **118**, in this example of FIG. **1**, electrodes and so on are not disposed. As a specific structural example, for example, on the circuit board **118** constituted of a glass epoxy substrate, a glass composite substrate, or the like, the electrodes **111**, **112** are formed of a conductive thin film of copper or the like. The electrodes **111**, **112** are disposed in parallel at positions separated by a predetermined distance d**1**. Further, a width D of the electrodes **111**, **112** including the distance d**1** is set to be narrower than a near field denoted by $\lambda/2\pi$ where λ is a wavelength of electric fields emitted from these electrodes.

Ends of inductors **113**, **114** are connected to ends in a lateral direction of the electrodes **111**, **112**, respectively, of the circuit board **118**. Further, other ends of the inductors **113**, **114** are connected to one ends of connection lines **115**, **116**, respectively. The connection lines **115**, **116** are disposed to avoid areas of the electrodes **111**, **112** and an area sandwiched between them, and are also disposed to extend in a direction to depart from these areas (leftward and downward direction in FIG. **1**). More particularly, they are disposed to avoid respective rectangular areas of the electrodes **111**, **112** and the area sandwiched between these two electrodes **111**, **112**, and also disposed to extend in the direction to depart from these areas. By disposing in this manner, interference between the electrodes **111**, **112** and the connection lines **115**, **116** is decreased, and thus decrease in transmission efficiency can be prevented. The connection lines **115**, **116** are, for example, constituted of a coaxial cable or a balanced cable. Note that other ends of the connection lines **115**, **116** are connected respectively to output terminals of a not-illustrated alternating-current power generating unit. By connecting the alternating-current power generating unit to the power transmission coupler **110** by the connection lines **115**, **116**, a power transmission device is constituted.

The power transmission coupler **110** constitutes a series resonance circuit with capacitance C of a capacitor formed by disposing the electrodes **111**, **112** across the predetermined distance d**1** and inductance L of the inductors **113**, **114**, and thus has a peculiar resonance frequency f_c due to them.

A power reception coupler **120** has the same structure as the power transmission coupler **110**, and is formed by disposing electrodes **121**, **122** constituted of a conductive member having a rectangular shape and inductors **123**, **124** on a front surface **128**A of a circuit board **128**, and connecting connection lines **125**, **126** to other ends of the inductors **123**, **124**. A resonance frequency f_c of a series resonance circuit due to capacitance C of a capacitor formed by the electrodes **121**, **122** and inductance L of the inductors **123**, **124** is set to be substantially the same as that of the power transmission coupler **110**. The connection lines **125**, **126** are, for example, constituted of a coaxial cable or a balanced cable. A not-illustrated load is connected to other ends of the connection lines **125**, **126** of the power reception coupler **120**. By connecting the load to the power reception coupler **120** by the connection lines **125**, **126**, a power reception device is constituted.

FIG. **2** is a view illustrating a state that the power transmission coupler **110** and the power reception coupler **120** are disposed to oppose each other. As illustrated in this view, the power transmission coupler **110** and the power reception coupler **120** are disposed so that the circuit boards **118**, **128** are in parallel across a distance d**2** and the front surfaces **118**A, **128**A of the circuit boards **118**, **128** oppose each other.

FIG. **3** is a diagram illustrating an equivalent circuit of the wireless power transmission system **1** illustrated in FIG. **2**. In FIG. **3**, an alternating-current power generating unit **211** generates and outputs alternating-current power with a frequency corresponding to the resonance frequency. A power supply unit load **212** exhibits a value equal to characteristic impedances of the connection lines **115**, **116** and the connection lines **125**, **126**, and has a value of Z**0**. An inductor **213** corresponds to the inductors **113**, **114** and has an element value of L**1**. A resistor **214** exhibits resistance which accompanies a transmission side circuit, mainly the inductor, and has an element value of R**1**. A capacitor **215** is a capacitor of an element value C**1** occurring between the electrodes **111**, **112**. A capacitor **221** is a capacitor of an element value C**2** occurring between the electrodes **121**, **122**. An inductor **222** corresponds to the inductors **123**, **124** and has an element value of L**2**. A resistor **223** exhibits resistance which accompanies a reception side circuit, mainly the inductor, and has an element value of R**2**. A load **224** is supplied with power outputted from the alternating-current power generating unit **211** and transmitted via the power transmission coupler and the power reception coupler. A capacitor **241** denotes a capacitor occurring between the electrodes **111**, **112** and the electrodes **121**, **122** and has an element value of Cm**1**. Note that the load **224** is, for example, constituted of a rectifying device, a secondary battery, and so on. Of course, it may be constituted of other elements.

Next, operations of the wireless power transmission system utilizing series resonance illustrated in FIG. **2** will be described. FIG. **4** is a diagram illustrating frequency characteristics of transmission efficiency η**21** ($=|S21|^2$) from the power transmission coupler **110** to the power reception coupler **120** and reflection loss η**11** ($=|S11|^2$), in the case where the power transmission coupler **110** and the power reception coupler **120** of the wireless power transmission system illustrated in FIG. **2** are disposed to oppose each other across a distance of 20 cm (the case where d**2**=20 cm). In this diagram, the horizontal axis denotes frequency (MHz) of transmitted alternating-current power, and the vertical axis denotes transmission efficiency. In the example illustrated in FIG. **4**, it can be seen that a transmission efficiency of about 95% is achieved around 27 MHz. Note that in FIG. **2**, for example, the inductors **113**, **114**, **123**, **124** are each wound 13 times and has an inductance value of 2.8 μH, sizes (D and L) of the circuit boards **118**, **128** are 250×250 mm, and the gap d**1** between the electrodes **111**, **112** and the electrodes **121**, **122** is 34.4 mm.

FIG. **5** illustrates a smith chart of impedance S**11** of the power transmission coupler **110** of the wireless power transmission system utilizing series resonance illustrated in FIG. **2**. In this case, a port impedance of the measuring apparatus is set to a value equal to a characteristic impedance Z**0** (real value) of a connection line. As illustrated in these diagrams, in the wireless power transmission system illustrated in FIG. **2**, a trajectory of impedance of the power transmission coupler **110** and the power reception coupler **120** passes near the center of circle of the smith chart, and thus power can be transmitted efficiently while suppressing reflections by setting to perform transmission near the center.

FIG. **6** is a view illustrating a state that the power reception coupler **120** of the wireless power transmission system illustrated in FIG. **2** is disposed by rotating 90 degrees counterclockwise. FIG. **7** is a diagram illustrating frequency characteristics of transmission efficiency η**21** from the power transmission coupler **110** to the power reception coupler **120** and reflection loss η**11** in the disposition state of FIG. **6**. As illustrated in FIG. **7**, the transmission efficiency η**21** becomes 0 and the reflection loss η**11** becomes a value close to 1, and thus most of the power inputted to the power transmission coupler **110** is reflected and not transmitted to the power reception coupler **120**. Further, as illustrated in FIG. **8**, it becomes a state that the input impedance S**11** is low, and a state that the impedance does not match. Thus, in the wireless power transmission system illustrated in FIG. **2**, power cannot be transmitted in a state that the power transmission coupler **110** and the power reception coupler **120** are orthogonal as illustrated in FIG. **6**. From the above, in the wireless power transmission system illustrated in FIG. **2**, when the power transmission coupler **110** and the power reception coupler **120** are rotated about an axis, it leads to deterioration in characteristics.

(B) Description of Embodiments of the Present Invention

Next, with reference to FIG. **9** and FIG. **10**, a structural example of a wireless power transmission system according to an embodiment of the present invention will be described. FIG. **9** is a perspective view of the embodiment, and FIG. **10** is a plan view seeing the embodiment illustrated in FIG. **9** from a Z direction. In the embodiment illustrated in FIG. **9** and FIG. **10**, a power transmission coupler **310** is constituted of a circular center electrode **311**, a ring-shaped annular electrode **312**, inductors **313**, **314**, and connection lines **315**, **316**, and a power reception coupler **320** is constituted of a circular center electrode **321**, a ring-shaped annular electrode **322**, inductors **323**, **324**, and connection lines **325**, **326**. In the examples of FIG. **9** and FIG. **10**, sizes of the respective elements constituting the power transmission coupler **310** and the power reception coupler **320** are the same. Of course, even when the sizes of the respective elements are different, power can be transmitted by adjusting the sizes so that the resonance frequency is the same. Note that although only the electrodes are illustrated in the examples of FIG. **9** and FIG. **10**, the electrodes can be formed on a substrate or base material formed of a glass epoxy substrate, a glass composite substrate, or the like, similarly to FIG. **1** and FIG. **2**.

Here, the center electrode **311** is constituted of a platy conductive member (for example, a member of copper, aluminum, or the like) having a circular shape with a radius r**1**. The annular electrode **312** is constituted of a platy conductive member having an annular shape with an outer radius r**2** and a width w. Note that the center electrode **311** and the annular electrode **312** are disposed on a same plane, and the distance between an outer periphery of the center electrode **311** and an inner periphery of the annular electrode **312** is d**1**. One end of the inductor **313** is connected to the center electrode **311**, and the other end is connected to one end of the connection line **315**. One end of the inductor **314** is connected to the annular electrode **312**, and the other end is connected to one end of the connection line **316**. The connection lines **315**, **316** are, for example, constituted of a coaxial cable or a balanced cable. Other ends of the connection lines **315**, **316** are connected respectively to output terminals of a not-illustrated alternating-current power generating unit. By connecting the alternating-current power generating unit to the power transmission coupler **310** by the connection lines **315**, **316**, a power transmission device is constituted. Note that a resonance frequency of a series resonance circuit due to capacitance C of a capacitor formed by the center electrode **311** and the annular electrode **312** and inductance L of the inductors **313**, **314** is f_c.

The center electrode **321** is constituted of a platy conductive member having a circular shape with a radius r**1**. The annular electrode **322** is constituted of a platy conductive member having an annular shape with an outer radius r2 and a width w. The center electrode **321** and the annular electrode **322** are disposed on a same plane, and the distance between an outer periphery of the circular center electrode **321** and an inner periphery of the annular electrode **322** is d**1**. Further, the plane on which the center electrode **311** and the annular electrode **312** are disposed and the plane on which the center electrode **321** and the annular electrode **322** are disposed are kept substantially in parallel. One end of the inductor **323** is connected to the center electrode **321**, and the other end is connected to one end of the connection line **325**. One end of the inductor **324** is connected to the annular electrode **322**, and the other end is connected to one end of the connection line **326**. The connection lines **325**, **326** are, for example, constituted of a coaxial cable or a balanced cable. Other ends of the connection lines **325**, **326** are connected respectively to input terminals of a not-illustrated load. By connecting the load to the power reception coupler **320** by the connection lines **325**, **326**, a power reception device is constituted. Note that a resonance frequency f_c of a series resonance circuit due to capacitance C of a capacitor formed by the center electrode **321** and the annular electrode **322** and inductance L of the inductors **323**, **324** is set to be the same as that of the power transmission coupler **310**.

FIG. **11** is a diagram illustrating frequency characteristics of transmission efficiency η**21** (=|S**21**|^2) from the power transmission coupler **310** to the power reception coupler **320** and reflection loss η**11** (=|S**11**|^2), in the case where the power transmission coupler **310** and the power reception coupler **320** of the wireless power transmission system illustrated in FIG. **9** and FIG. **10** are disposed to oppose each other across a distance of 20 cm (the case where d2=20 cm). More particularly, the radius r**1** of the center electrodes **311**, **321** is 7 cm, the diameter r**2** of outer peripheries of the annular electrodes **312**, **322** is 24 cm, the width w of the annular electrodes **312**, **322** is 1.5 cm, and d**1** is set to 15.5 cm. Further, the inductors **313**, **314**, **323**, **324** are each wound 13 times and set to have an inductance value of 2.8 μH. In FIG. **11**, the horizontal axis denotes frequency (MHz) of transmitted alternating-current power, and the vertical axis denotes transmission efficiency. In the example illustrated in FIG. **9**, a transmission efficiency of about 96% is achieved around 27 MHz.

FIG. **12** illustrates a smith chart of impedance S**11** of the power transmission coupler **310** of the wireless power transmission system illustrated in FIG. **9** and FIG. **10**. In this case, a port impedance of the measuring apparatus is set to a value equal to a characteristic impedance Z**0** (real value) of a connection line. As illustrated in these diagrams, in the wireless power transmission system illustrated in FIG. **9** and FIG. **10**, a trajectory of impedance of the power transmission coupler **310** passes near the center of circle of the smith chart, and thus power can be transmitted efficiently while suppressing reflections by setting to perform transmission near the center.

That is, in the embodiment illustrated in FIG. **9**, the center electrode **311** and the annular electrode **312** are coupled by electric field resonance to the center electrode **321** and the annular electrode **322**, and alternating-current power is transmitted by an electric field from the center electrode **311** and the annular electrode **312** to the center electrode **321** and the annular electrode **322**. That is, in the embodiment illustrated in FIG. **9**, since the center electrode **311** and the annular electrode **312** and the center electrode **321** and the annular electrode **322** are disposed across the distance d**2** shorter than λ/2π as a near field, the center electrode **321** and the annular electrode **322** are disposed in an area where electric field components emitted from the center electrode **311** and the annular electrode **312** are dominant. Further, a resonance frequency due to the capacitor formed between the center electrode **311** and the annular electrode **312** and the inductors **313**, **314** and a resonance frequency due to the capacitor formed between the center electrode **321** and the annular electrode **322** and the inductors **323**, **324** are set to be substantially equal. Thus, since the center electrode **311** and the annular electrode **312** are coupled by electric field resonance to the center electrode **321** and the annular electrode **322**, the alternating-current power is transmitted efficiently from the power transmission coupler **310** to the power reception coupler **320** by the electric field.

FIG. **13** is a diagram illustrating an electric field distribution of the embodiment illustrated in FIG. **9**, and FIG. **14** illustrates the electric field distribution of FIG. **10**. In these diagrams, the direction of an arrow indicates the direction of an electric field, and the size of an arrow indicates the intensity of an electric field. As illustrated in these diagrams, electric fields in the vicinities of the power transmission coupler **310** and the power reception coupler **320** are formed axially symmetrically with respect to the center axis of these couplers. Accordingly, when the power transmission coupler **310** and the power reception coupler **320** are rotated in either direction about the axis, deterioration in characteristics is small.

FIG. **15** is a view illustrating a state that the power reception coupler **320** is rotated 90 degrees counterclockwise in the embodiment illustrated in FIG. **9**. Further, FIG. **16** is a diagram illustrating frequency characteristics of transmission efficiency η**21** from the power transmission coupler **310** to the power reception coupler **320** and reflection loss η**11** in the state illustrated in FIG. **15**, and FIG. **17** is a smith chart of impedance S**11** of the power transmission coupler **310** in the same state. As illustrated in FIG. **16**, a transmission efficiency at 27 MHz is about 96%, and there is no deterioration in characteristics from the state illustrated in FIG. **9**. Further, as illustrated in FIG. **17**, also regarding the input impedance, there is no change from the state illustrated in FIG. **9**.

As described above, according to the embodiment of the present invention, it is possible to wirelessly transmit power from the power transmission coupler **310** to the power reception coupler **320** with high efficiency of 90 percent or more. Further, according to the embodiment of the present invention, even when the electrodes are rotated about the axis, changes in characteristics can be made quite small.

(C) Description of Variant Embodiments

The above embodiment is an example, and it is needless to mention that the present invention is not limited to the cases as described above. For example, in the above embodiment, the completely round center electrodes **311**, **321** and the completely round annular electrodes **312**, **322** are used, but for example, as illustrated in FIG. **18**, the center electrodes **311**, **321** may have cutouts **311***a*, **321***a* extending from the outer periphery to the center, and the annular electrodes **312**, **322** may have cutouts **312***a*, **322***a* in a part. FIG. **19** illustrates frequency characteristics of transmission efficiency η**21** and reflection loss η**11** of the embodiment illustrated in FIG. **18**, and FIG. **20** is a smith chart of input impedance S**11**. From comparison of these diagrams with FIG. **11** and FIG. **12**, changes in characteristics hardly occur even when the cutouts are provided. Thus, when such cutouts are provided, the transmission efficiency hardly deteriorates.

FIG. **21** is a view illustrating a state that the power reception coupler **320** of FIG. **18** is rotated 90 degrees counterclockwise. In such a state, the positions of the cutouts **311***a*, **321***a* and the cutouts **312***a*, **322***a* do not correspond. However, changes in characteristics hardly occur even in such a state. More particularly, FIG. **22** illustrates frequency characteristics of transmission efficiency η**21** and reflection loss η**11** of the embodiment illustrated in FIG. **21**, and FIG. **23** is a smith chart of input impedance S**11**. From comparison of these diagrams with FIG. **19** and FIG. **20**, changes in characteristics hardly occur when the power reception coupler **320** is rotated. Of course, the same is true in the case where the power transmission coupler **310** is rotated. Note that in the example of FIG. **18**, the cutouts are provided in all of the center electrodes **311**, **321** and the annular electrodes **312**, **322**, but the cutouts may be provided in at least one of them.

FIG. **24** illustrates another variant embodiment. Specifically, FIG. **24** illustrates an embodiment in which the center electrodes **311**, **321** are made annular by providing through holes **311***b*, **321***b* in the center electrodes **311**, **321**, respectively. In this example, the through holes **311***b*, **321***b* with a to radius r**3** are formed in the centers of the center electrodes **311**, **321**, respectively. Note that the other structure is the same as in FIG. **9**. FIG. **25** illustrates frequency characteristics of transmission efficiency η**21** and reflection loss η**11** of the embodiment illustrated in FIG. **24**, and FIG. **26** is a smith chart of input impedance S**11**. From comparison of these diagrams with FIG. **11** and FIG. **12**, changes in characteristics hardly occur even when the through holes **311***b*, **321***b* are provided in the center electrodes **311**, **321**. Thus, when such through holes **311***b*, **321***b* are provided, the transmission characteristic hardly deteriorates.

FIG. **27** is a view illustrating a state that the power reception coupler **320** of FIG. **24** is rotated 90 degrees counterclockwise. In the embodiment of FIG. **24**, since the through holes **311***b*, **321***b* are formed axially symmetrically, electric fields formed by the power transmission coupler **310** and the power reception coupler **320** become axially symmetrical similarly to FIG. **13** and FIG. **14**. Thus, when the power reception coupler **320** is rotated as illustrated in FIG. **27**, changes in characteristics hardly occur. More particularly, FIG. **28** illustrates frequency characteristics of transmission efficiency η**21** and reflection loss η**11** of the embodiment illustrated in FIG. **27**, and FIG. **29** is a smith chart of input impedance S**11**. From comparison of these diagrams with FIG. **25** and FIG. **26**, changes in characteristics hardly occur even when the power reception coupler **320** is rotated. Of course, the same is true in the case where the power transmission coupler **310** is rotated. Note that in the example of FIG. **24**, the through holes are provided in both the center electrodes **311**, **321**, but they may be provided in at least one of them. Further, cutouts may be provided as necessary in at least one of the center electrodes **311**, **321** and the annular electrodes **312**, **322** as described above.

Further, in the above embodiments, the center electrode **311** and the center electrode **321** have the same size and the annular electrode **312** and the annular electrode **322** have the same size, but they may have different sizes. Further, the center electrodes **311**, **321** and the annular electrodes **312**, **322** are completely round, but they may be, for example, elliptic or polygonal. Further, the center electrode **311** and the annular electrode **312** and the center electrode **321** and the annular electrode **322** are disposed on the same planes respectively, but for example, they may be disposed to be displaced in an axial direction. Further, the center electrodes **311**, **321** and the annular electrodes **312**, **322** may be of curved or bent shape instead of the plate shape, or may be of a three-dimensional shape such as a sphere. Moreover, it may have a three-dimensional shape extended in an axial direction. Further, it may have a three-dimensional shape extended in an axial direction in a state of having cutouts or through holes.

Further, in the above embodiments, the inductors **313**, **314** reside in both between the connection line **315** and the center electrode **311** and between the connection line **316** and the annular electrode **312**, but an inductor may reside in only one of them. Similarly, in the power reception coupler **320**, the inductors **323**, **324** reside in both between the connection line **325** and the center electrode **321** and between the connection line **326** and the annular electrode **322**, but an inductor may reside in only one of them. Further, in the above-described embodiment, the inductors are formed by winding conductor lines in a columnar shape, but it may be formed by, for example, one having a shape meandering on a plane as used in a microstrip line, or one having a spiral shape on a plane.

Further, the above-described embodiments have the circular m electrodes and the annular electrodes, but for example, it is also possible to constitute them of cylindrical electrodes as illustrated in FIG. **30**. The example of FIG. **30** has a power transmission coupler **410** and a power reception coupler **420**. Here, electrodes **411**, **412** constituting the power transmission coupler **410** are constituted of a conductive member having a is cylindrical shape with a radius **r1**. Note that although cylindrical members are used in the example of FIG. **30**, it may be formed by curving rectangular conductive members to have a radius **r1**. In this case, ends of the conductive members may be either in contact or not in contact. The electrodes **411**, **412** are disposed in parallel at positions separated by a predetermined distance d**1** in an axial direction (X direction in the view). Further, a width D of the electrodes **411**, **412** including the distance d**1** is set to be narrower than a near field indicated by λ/2π where the wavelength of electric fields emitted from these electrodes is λ. The electrodes **411**, **412** are fixed via a not-illustrated insulating member (for example, a dielectric substrate). Further, the electrodes **411**, **412** are connected to an alternating-current power supply **417** via inductors **413**, **414** and connection lines **415**, **416**. Note that the power transmission coupler **410** is constituted of the electrodes **411**, **412** and the inductors **413**, **414**.

Electrodes **421**, **422** constituting the power reception coupler **420** are constituted of a conductive member having a cylindrical shape with a radius r**2** (<r**1**). Note that although cylindrical members are used in the example of FIG. **30**, it may be formed by curving rectangular conductive members to have a radius r**2**. In this case, ends of the conductive members may be either in contact or not in contact. The electrodes **421**, **422** are disposed in parallel at positions separated by a predetermined distance d**2** in an axial direction (X direction in the view). Further, the electrodes **421**, **422** are disposed so that their center axis corresponds to that of the electrodes **411**, **412**. Further, a width D of the electrodes **421**, **422** including the distance d**2** is set to be narrower than a near field indicated by λ/2π where the wavelength of electric fields emitted from these electrodes **411**, **412** is λ. The electrodes **421**, **422** are fixed via a not-illustrated insulating member (for example, a dielectric substrate). A gap between the electrodes **421**, **422** and the electrodes **411**, **412** is d**3**. Further, the electrodes **421**, **422** are connected to a load **427** via inductors **423**, **424** and connection lines **425**, **426**. The power reception coupler **420** is constituted of the electrodes **421**, **422** and the inductors **423**, **424**. Note that a resonance frequency of the resonance circuit constituted of the electrodes **411**, **412** and the inductors **413**, **414** illustrated in FIG. **30** and a resonance frequency of the resonance circuit constituted of the electrodes **421**, **422** and the inductors **423**, **424** are set to be the same, and their principle of operation is similar to that of the case of FIG. **1**. According to the embodiment illustrated in FIG. **30**, power can be transmitted efficiently from the power transmission coupler **410** to the power reception coupler **420**, and even when the power transmission coupler **410** or the power reception coupler **420** rotates about the center axis, decrease in transmission characteristics is small. Note that although the electrodes **411**, **412**, **421**, **422** are circular cylinders in FIG. **30**, they may be polygonal cylinders. Further, in the example of FIG. **30**, the electrodes **411**, **412** are structured to be longer in axial direction length than the electrodes **421**, **422**, but they may be the same, or the electrodes **421**, **422** may be structured to be longer in axial direction length than the electrodes **411**, **412**.

EXPLANATION OF REFERENCE SIGNS

310 power transmission coupler
311 center electrode (first electrode)
311*a* cutout
311*b* through hole
312 annular electrode (second electrode)
312*a* cutout
313, **314** inductor
315, **316** connection lines
320 power reception coupler
321 center electrode (third electrode)
321*a* cutout
321*b* through hole
322 annular electrode (fourth electrode)
322*a* cutout
323, **324** inductor
325, **326** connection line
410 power transmission coupler
411 electrode (first electrode)
412 electrode (second electrode)
420 power reception coupler
421 electrode (third electrode)
422 electrode (fourth electrode)

The invention claimed is:

1. A wireless power transmission system transmitting alternating-current power from a power transmission device to a power reception device, wherein

the power transmission device comprises:

a first and a second electrode which are disposed across a predetermined distance, in which a total width including the predetermined distance is λ/2π or less as a near field, the first and the second electrode each having a rotationally symmetrical shape with respect to a common center axis;

a first and a second connection line electrically connecting the first and the second electrode and two output terminals of an alternating-current power generating unit, respectively; and

a first inductor residing between the first and the second electrode and at least one of the two output terminals of the alternating current power generating unit, and

the power reception device comprises:

a third and a fourth electrode which are disposed across a predetermined distance, in which a total width including the predetermined distance is λ/2π or less as a near field, the third and the fourth electrode each having a rotationally symmetrical shape with respect to a common center axis;

a third and a fourth connection line electrically connecting the third and the fourth electrode and two input terminals of a load, respectively; and

a second inductor residing between the third and the fourth electrode and at least one of the two input terminals of the load, wherein:

the electrodes of the power transmission device and the power reception device are disposed to oppose each other across a distance of λ/2π or less as a near field,

a resonance frequency of a coupler constituted of the first and the second electrode and the first inductor and a resonance frequency of a coupler constituted of the third and the fourth electrode and the second inductor are set to be substantially equal, the first electrode has a first platy polygonal or circular shape, and the second electrode has a second platy polygonal or circular annular shape disposed to surround the first electrode and is disposed on a same plane to have a first center axis corresponding to that of the first electrode,

the third electrode has a third platy polygonal or circular shape, and the fourth electrode has a fourth platy polygonal or circular annular shape disposed to surround the third electrode and is disposed on a same plane to have a second center axis corresponding to that of the third electrode, and

the first and the second electrode and the third and the fourth electrode are disposed to oppose each other across a distance of $\lambda/2\pi$ or less as a near field.

2. The wireless power transmission system according to claim **1**, wherein at least one of the first to the fourth electrode has a cutout in a radial direction.

3. The wireless power transmission system according to claim **1**, wherein at least one of the first electrode and the third electrode has an annular shape.

4. The wireless power transmission system according to claim **1**, wherein at least one of the first to the fourth electrode has a three-dimensional structure extending in an axial direction.

* * * * *